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Design and Construction of a Fluidized-bed Combustion Sampling and Analytical Test Rig

Acurex Corp, Mountain View, CA Energy and Environmental Div

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

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16. ABSTRACT The report describes the design, construction, and installation of a fluidized-bed coal combustion sampling and analytical test rig in the High Bay Area (Wing G) of EPA's Industrial Environmental Research Laboratory (IERL), Research Triangle Park, North Carolina. The rig, to be used by IERL to investigate the emission characteristics of fluidized-bed combustors, was designed for maximum flexibility, accuracy, and utility. System operating ranges are: coal feedrate--10 to 50 kg/hr; sorbent feedrate--zero to 25 kg/hr; excess air--10 to 300%; bed temperature--750 to 1100 C; and fluidizing velocity--1 to 5 mps. The program included four phases: conceptual design; final design; purchase, fabrication, and installation; and checkout, testing, and documentation. After installation, an acceptance test demonstrated that the system had been completed in accordance with the approved design, and that all equipment was properly installed and corrected to serve its intended purpose.

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Fluidized Bed Processing			13H	
Test Equipment			14B	
Sampling				
Analyzing				

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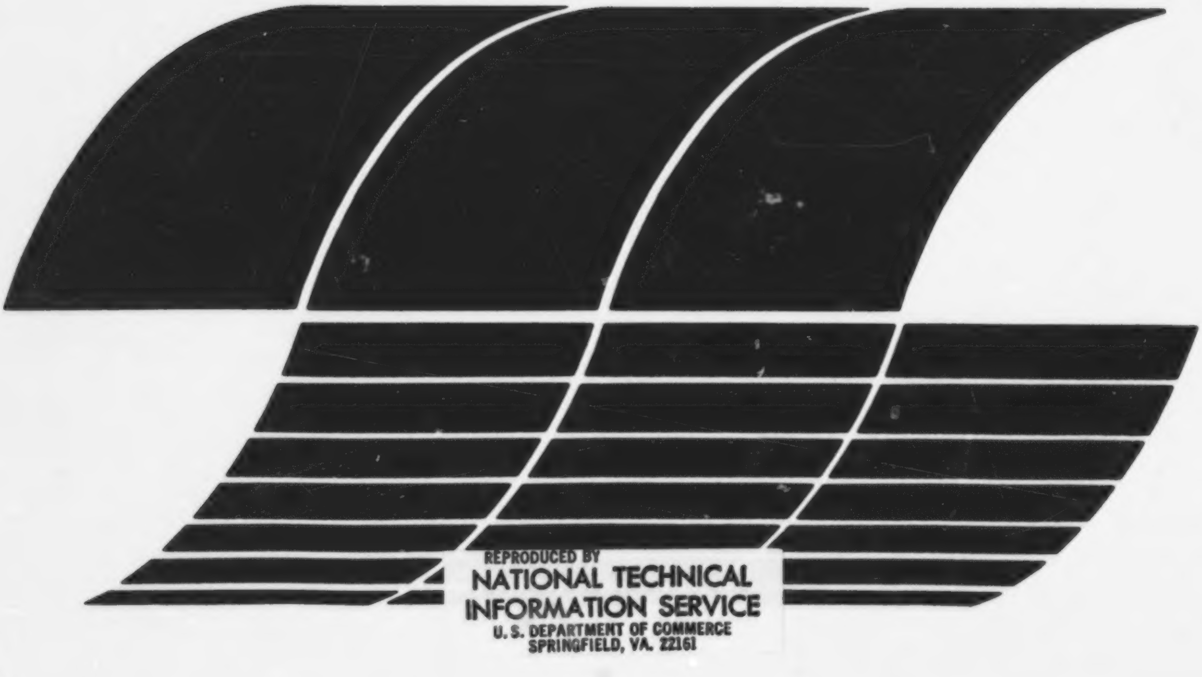

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EPA-600/7-78-166

August 1978

Design and Construction of a Fluidized-bed Combustion Sampling and Analytical Test Rig

by

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Contract No. 68-02-2170
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ABSTRACT

A Fluidized-Bed Coal Combustion Sampling and Analytical Test Rig was designed, fabricated and installed in the High Bay area (Wing G) of the Industrial Environmental Research Laboratory (IERL) at Research Triangle Park, North Carolina to be used by IERL for research programs. It is a research tool where the design philosophy was based on considerations of flexibility, accuracy and utility. The system operating ranges are:

Coal feedrate - 10 to 50 kg/hr (22 to 110 lbm/hr)
Sorbent feedrate - 0 to 25 kg/hr (0 to 55 lbm/hr)
Excess air - 10 to 300 percent
Bed temperature - 750°C to 1100°C (1380°F to 2010°F)
Fluidizing velocity - 1 to 5 mps (3 to 16 fps)

The purpose of this project was to provide EPA with the capability to investigate the emission characteristics of fluidized-bed combustors.

The program was completed in three phases: preparation of the conceptual design; preparation of the final design; purchase, fabrication, installation, and checkout, testing and documentation.

During the conceptual design phase the capability of sampling the composition of all process streams was especially considered. Recommendations were made for sampling and analytical procedures and equipment to measure pollutants of interest. At least four particulate control devices were to be incorporated in the design. They were a conventional inertial separator, a "tornado-type" cyclone, a fabric filter and an electrostatic precipitator. Emphasis was placed on the approximation of full-scale conditions as closely as possible and to minimize the manpower required to conduct tests and change conditions between tests.

The final design was carried out in sufficient detail to enable the purchase, fabrication and installation of the unit.

The equipment was procured, fabricated and installed in accordance with the requirements set forth in the drawings and specifications in Phase II of the program.

Upon completion of the installation an acceptance test was conducted to demonstrate that the system was completed in accordance with the approved design and that all equipment was properly installed to serve its intended purpose.

An operating manual and as-built drawings have been submitted.

This work was submitted in fulfillment of Contract Number 68-02-2170 by Acurex Corporation, Energy and Environmental Division under sponsorship of the Environmental Protection Agency.

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The personnel of the Industrial Environmental Research Laboratory of the EPA are recognized for their role in achieving this goal. Special thanks go to J. Wasser the EPA Project Officer and Walt Steen.

SECTION 1
INTRODUCTION

The need for environmentally acceptable coal-based steam and power generation processes gave rise to this project. As stated in the Scope of Work.

> "Fluidized-bed combustion (FBC) offers the potential for coal-based steam and power generation with low environmental impact, and at the same time with improved thermal efficiency and reduced manpower costs in comparison with conventional boilers. It is important to completely characterize emissions from FBC units. The purpose of this project is to provide EPA with the capability to investigate the emission characteristics of fluidized-bed combustors. The major goals of the test rig schedule are:
>
> - Sampling the wide range of potential contaminants
> - Testing alternative sampling and analytical techniques
> - Testing alternative control devices."

The contract called for the design, fabrication and installation in the High Bay area (Wing G) of the Industrial Environmental Research Laboratory (IERL) at Research Triangle Park, North Carolina of a fluidized-bed combustion sampling and analytical test rig and auxiliary equipment that would be used for IERL in-house research programs. The test rig was to be a research tool and the design philosophy should stress operational feasibility, accuracy and utility. Flexibility was required to allow the operation in a wide range of interest, accuracy to be able to draw significant conclusions from the experiments and utility to allow economic operation of the facility.

The program called for a program in three phases.

Phase I : Determination of Conceptual Design
Phase II : Preparation of Final Design and
Phase III: Purchase, Fabrication and Installation

The conceptual design considered specifically the identification of requirements and based upon these requirements a conceptual design was prepared. The requirements were the approximation of full-scale conditions, the capability to sample the composition of all process input and output streams, recommendations of sampling and analytical procedures, the inclusion of four particulate control devices, the ease of subsequent additions and testing of control devices, the flue and combustion conditions and considerations of solids handling.

Based upon the requirements identified a conceptual design was prepared and submitted. Included in the design package were schematic drawings and flow sheets, drawings and specifications of key components, material and heat balances, equipment and instrument lists and discussions of methods of solids handling and subsequent addition of add-on control devices.

Upon completion and approval of the conceptual design the final design was generated. Detailed component and construction drawings were prepared along with equipment duty and performance specifications. The final process flow analysis verified the material and energy balance. The fate of all input and output streams was determined and a survey of new material sources and prices was conducted.

The final design was approved and the Phase III begun and completed. Tasks completed under the Phase III program were the hardware, fabrication and installation, the preparation of an operating manual, personnel training, the acceptance test and as-built drawings.

The objective of the program was accomplished. Section 2 of the report details the fluidized-bed sampling and analytical test rig construction and Section 3 the operation of the test rig.

The procedures and equipment to be used for sampling and analysis are discussed in Section 4.

Section 5 discusses the acceptance test and results and Section 6 the raw material sources and prices.

SECTION 2

EQUIPMENT DESCRIPTION

2.1 GENERAL ARRANGEMENT

The FBC Test Rig located at Research Triangle Park in the Wing G Facility was built to allow the evaluation of a number of different pollution control devices for fluidized bed flue gas control applications. The fluidized bed essentially provides the flue gases to be controlled. To permit comparison studies to be conducted, control devices can be exchanged by connecting these devices onto convenient locations in the system. All major components in the system were placed along the Wing G mezzanine floor to allow easy access to the flue gas ducting for sampling and servicing. The following requirements were considered important in the design:

- Size of components
- Reconfiguration capability
- Normal traffic patterns
- Solids handling and storage
- Forklift accessibility
- Sampling port location and sampling convenience

The general arrangement drawings presented in Figures 2-1 through 2-4 show the FBC Test Rig major components. The major features of the subsystems are briefly presented below.

- Combustion unit
  - 38 x 38 cm (15 x 15 in) combustor area
  - 20.3 cm (8 in) refractory

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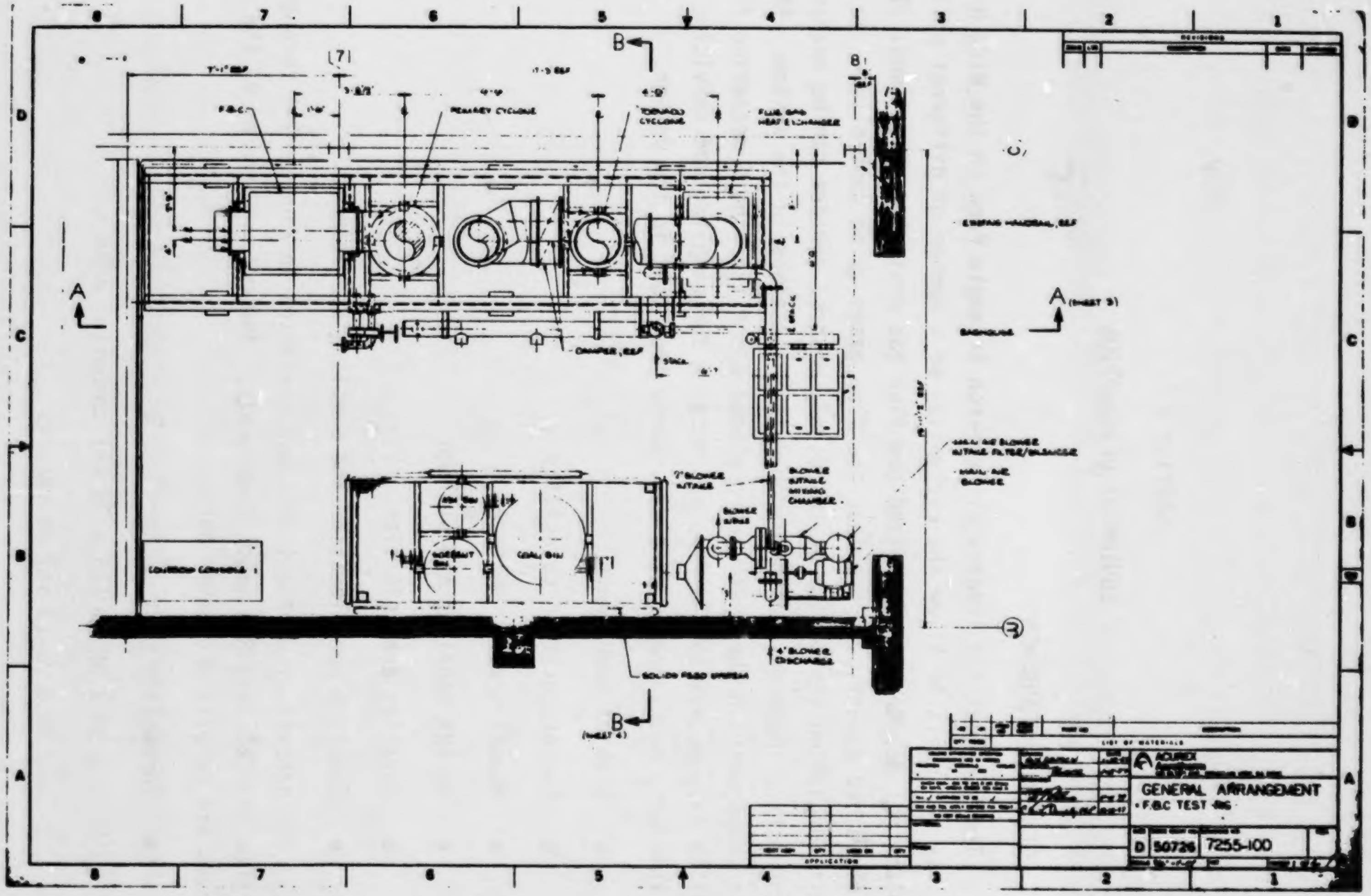
F.B.C.
PRIMARY CYCLONE
TORNADO CYCLONE
FLUE GAS HEAT EXCHANGER
DAMPER, REF
STACK
BAGHOUSE
EXISTING HANDRAIL, REF
A (SHEET 3)
MAIN AIR BLOWER INTAKE FILTER/SILENCER
MAIN AIR BLOWER
BLOWER INTAKE MIXING CHAMBER
7" BLOWER INTAKE
BLOWER INTAKE
SORBENT BIN
COAL BIN
CONTROL CONSOLE
SOLIDS FEED SYSTEM
4" BLOWER DISCHARGE
B (SHEET 4)
REVISIONS
LIST OF MATERIALS
APPLICATION
ACUREX
GENERAL ARRANGEMENT
F.B.C TEST RIG
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Figure 2-1. General arrangement drawing.

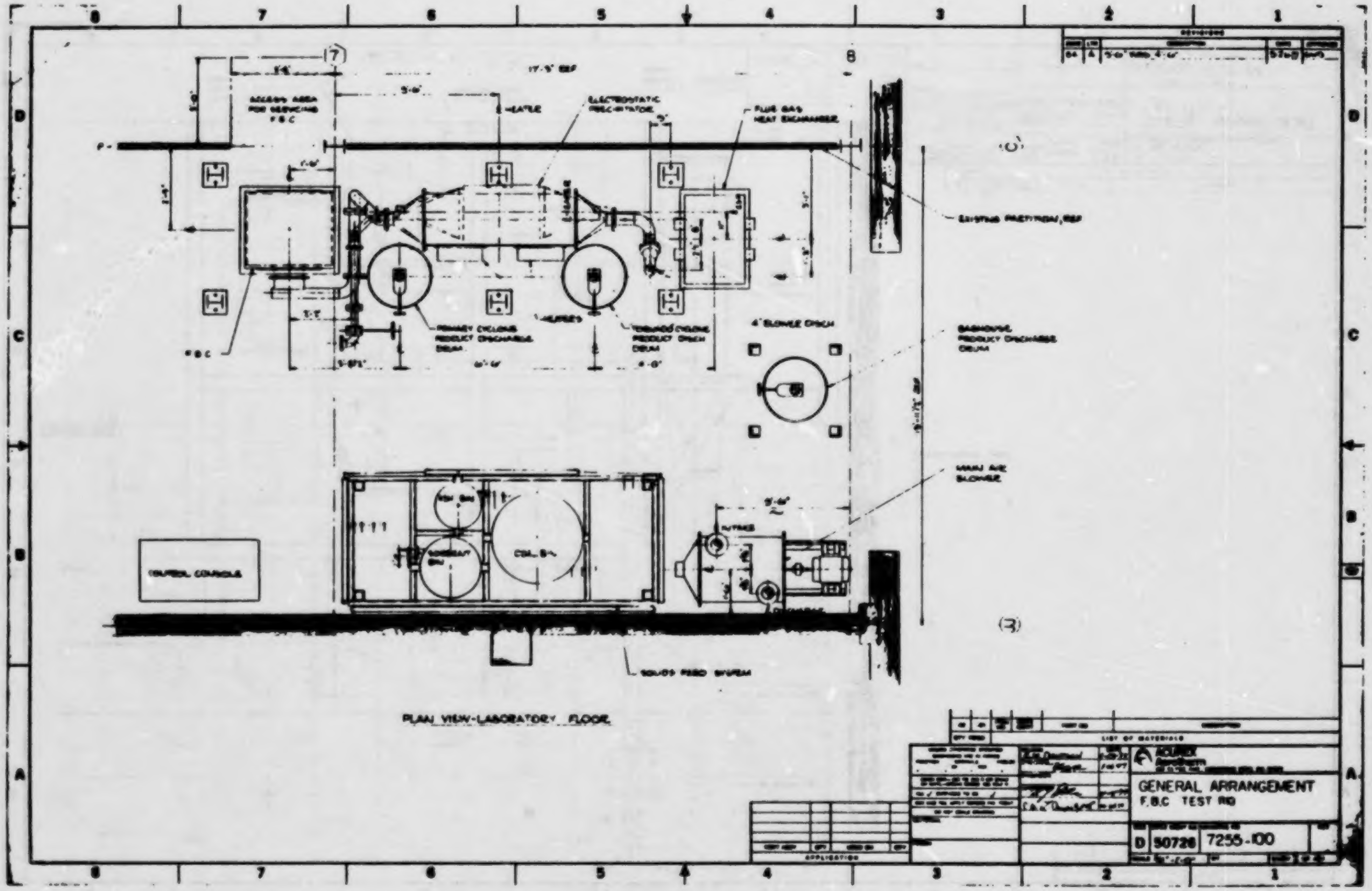
ACCESS AREA FOR SERVICING F.B.C
F.B.C
17'-5" REF
HEATER
ELECTROSTATIC PRECIPITATOR
FLUE GAS HEAT EXCHANGER
EXISTING PARTITION, REF
PRIMARY CYCLONE PRODUCT DISCHARGE DRUM
SECONDARY CYCLONE PRODUCT DISCH DRUM
4" BLOWER DISCH
BAGHOUSE PRODUCT DISCHARGE DRUM
MAIN AIR BLOWER
CONTROL CONSOLE
COAL BIN
SOLIDS FEED SYSTEM
PLAN VIEW-LABORATORY FLOOR
LIST OF MATERIALS
APPLICATION
ACUREX
GENERAL ARRANGEMENT
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Figure 2-2. General arrangement drawing.

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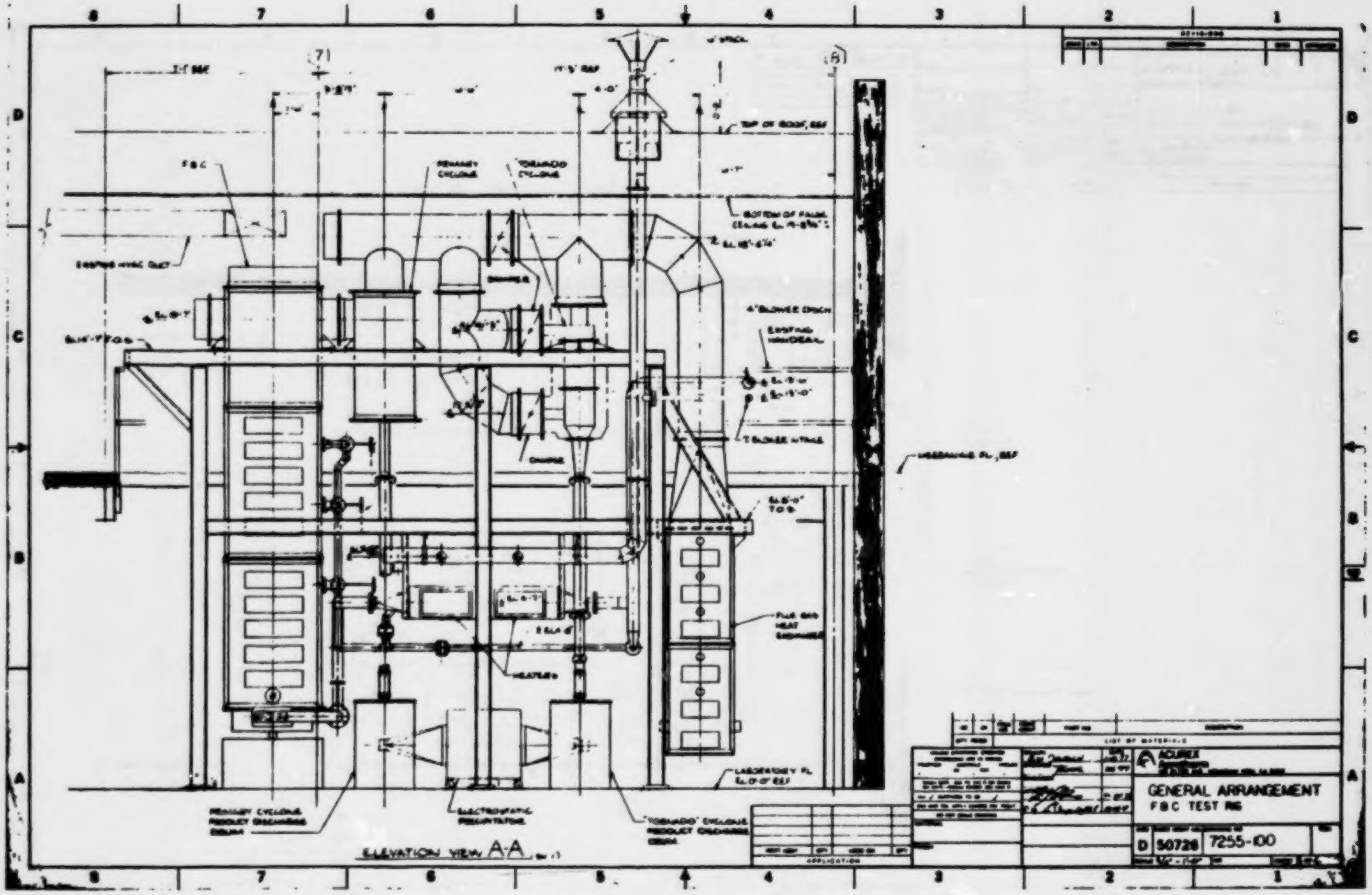
F B C
PRIMARY CYCLONE
"TORNADO" CYCLONE
DAMPER
DAMPER
EXISTING HVAC DUCT
TOP OF ROOF, REF
BOTTOM OF FALSE CEILING
4" BLOWER DISCH
EXISTING HANDRAIL
BLOWER INTAKE
MEZZANINE FL, REF
FLUE GAS HEAT EXCHANGER
HEATERS
LABORATORY FL EL 0'-0" REF
PRIMARY CYCLONE PRODUCT DISCHARGE DRUM
ELECTROSTATIC PRECIPITATOR
"TORNADO" CYCLONE PRODUCT DISCHARGE DRUM
ELEVATION VIEW A-A
LIST OF MATERIALS
ACUREX
GENERAL ARRANGEMENT
F B C TEST RIG
D
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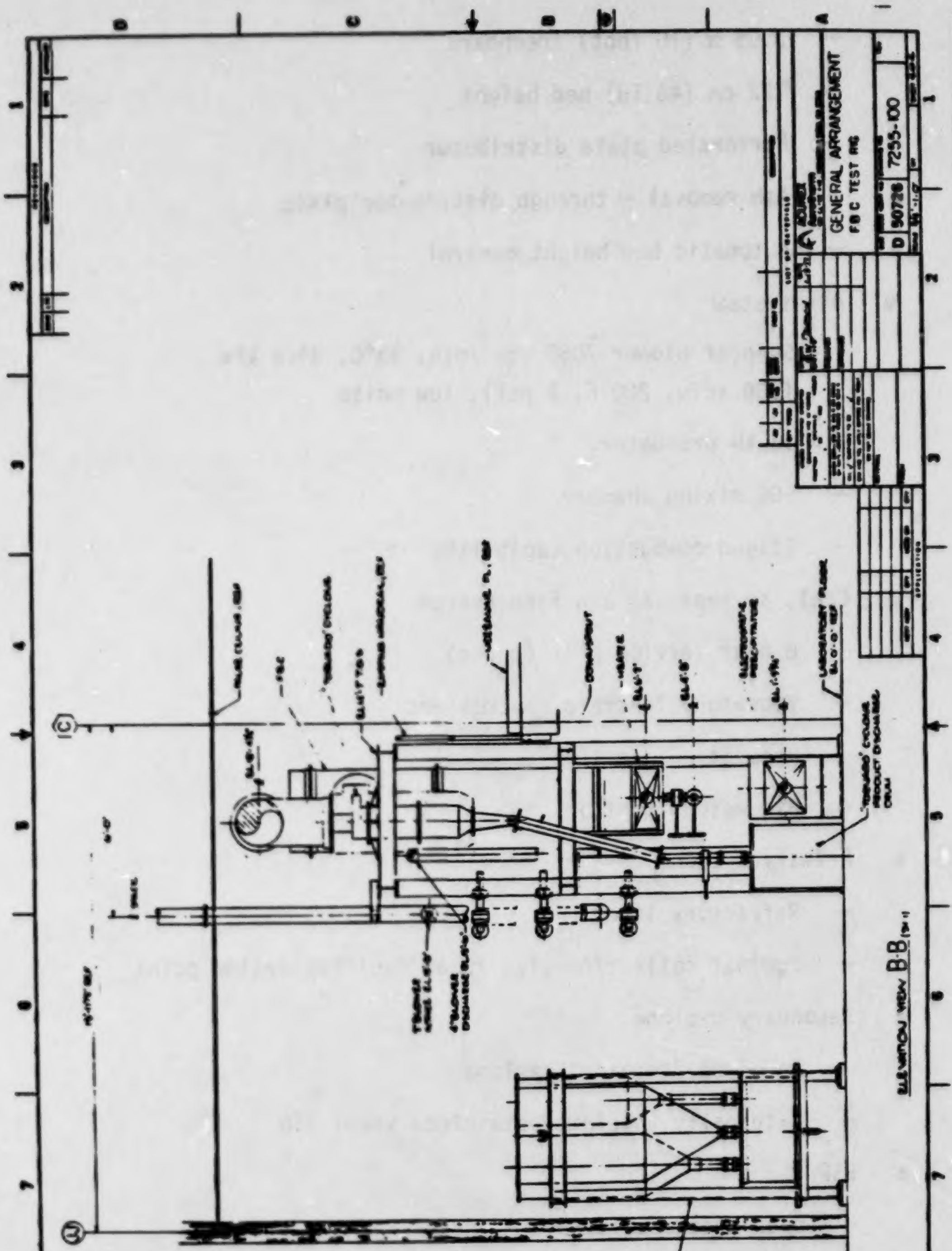
Figure 2-3. General arrangement drawing.


GENERAL ARRANGEMENT
F.B.C. TEST RIG
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ELEVATION VIEW B-B

Figure 2-4. General arrangement drawing.

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  - 3.05 m (10 foot) freeboard
  - 122 cm (48 in) bed height
  - Perforated plate distributor
  - Ash removal — through distributor plate
  - Automatic bed height control
- Air system
  - Spencer blower 7080 sdm^3/min, 93°C, 34.5 kPa (250 scfm, 200°F, 5 psi), low noise
  - 96 kW preheater
  - FGR mixing chamber
  - Staged combustion capability
- Coal, sorbent and ash feed system
  - 8 hour service bins (three)
  - Vibratory feedrate controllers
  - Pneumatic injection
  - Bin weight monitors
- Primary cyclone
  - Refractory lined
  - Nominal collection size 7μ at facility design point
- Secondary cyclone
  - Aerodyne "tornado" cyclone
  - Externally insulated stainless steel 310
- ESP
  - Double chamber design
  - Temperature rating to 260°C (500°F)
- Baghouse
  - Reverse pulse

  - 6.8 m^2 (73 ft^2) teflon felt material
  - Temperature rating to 260°C (500°F)
- Flue gas heat exchangers
  - Refractory-lined housing
  - Water-cooled cooling modules
  - Bare tube design
  - First two modules with double pitch to prevent clogging by flyash
  - Manual soot blowing lance
- Control system
  - Manual control
  - Safety interlocks
  - Alarm lights
  - Automatic heater temperature control
  - Pressure and temperature readouts
  - Weight readouts

The FBC test rig is designed to take full advantage of the available space. The 122 cm (4 foot) bed height and the 3.05 m (10 foot) freeboard are the maximum that could be accommodated below the false ceiling in the EPA Wing G Laboratory. The components of the rig are placed to allow access to the combustor and other heavy parts by forklift for servicing or for a configuration change. All major components are placed along the mezzanine. By placing the flue gas ducting along the mezzanine, the design allows sampling from that floor without requiring inconvenient, costly, and dangerously high platforms.

In addition, the unit is designed to be used with all or only some of the components onstream. Provisions have been made to enable the operator to bypass or change the flow through the secondary cyclone by adjusting three damper valves to the appropriate positions. The secondary control devices can also be evaluated in parallel, series, or separately by connecting them in the desired configuration with flexible ducting. Four exit ports are provided on the flue gas heat exchanger to connect secondary control devices. The stack is equipped with several equipment ports and sampling ports to gain this versatility.

The baghouse has been designed to be placed on rollers to enable the operator to clear the central area quickly should access from the outside be required. This would normally not be the case while the facility is operating. Access by forklift is only required for configuration changes and servicing of the feed bins; both of these activities can be accomplished by entering the area from the other side.

All components of the FBC test rig have been designed to reduce the labor and minimize the chance of injury to the operator. Controls and serviced components are easily accessible, and all high-temperature surfaces are insulated to reduce heat loss and make them safe for personnel.

2.2 COMBUSTOR

The major component in the FBC test rig is the combustor. As shown in Figure 2-5, it consists of the following elements:

- Combustor section
- Freeboard chamber
- Distributor plate
- Heat exchangers
- Air plenum box
- Bed height and temperature sensors
- Sampling and view ports
- Injection ports
- Ash removal system

Combustor Section

The combustor section houses the fluidized bed during operation. The combustor shell measures 91.5 cm (36 inches) wide, 79 cm (31 inches) deep, and 152 cm (60 inches) high. The shell is lined with mineral wool and refractory of minimum 20 cm (8 inch) thickness. The refractory used is Harbison Walker

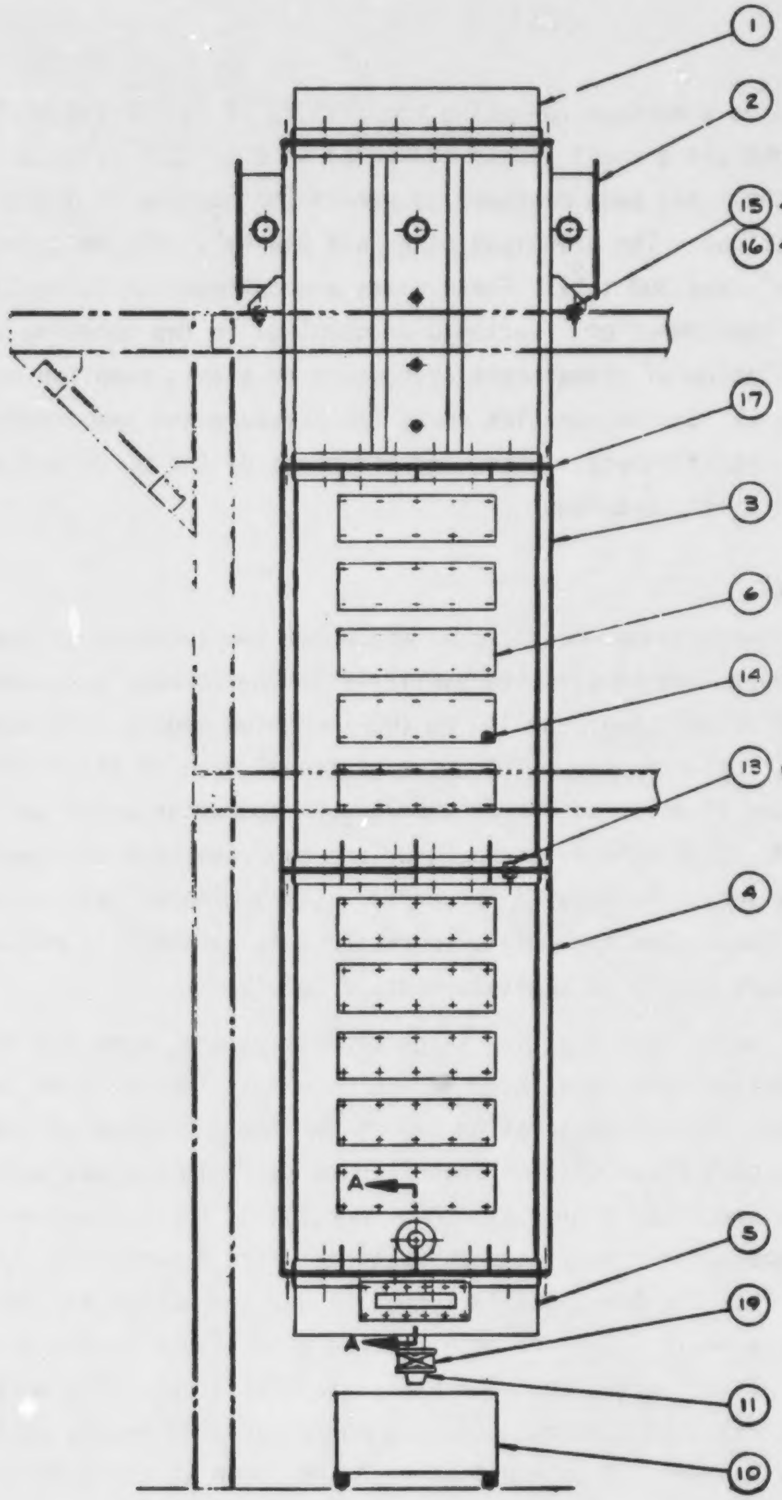
1
2
15 4 PLCS
16 4 PLCS
17
3
6 10 PLCS
14 184 PLCS
13 84 PLCS
4
A
5
19
A
11
10

Figure 2-5. Combustor.

40-64. It features a maximum operating temperature of 1430°C (2600°F), low iron oxide content and a small linear change of -0.2 to -0.6 percent at 815°C (1500°F). The shell has been designed to permit the casting of different combustor cross sections. The principal sizes are 968 cm^2, 1451 cm^2, and 1935 cm^2 (150 in^2, 225 in^2, and 300 in^2). These sizes are optimum for the noted heat release rate of the combustor. Rectangular openings in two opposing sides allow the installation of either heat exchangers or sight, sampling or injection ports. The third side contains ports for pressure and temperature measurement instrument installations. Sizes and locations of the ports are noted on the respective facility drawings.

Freeboard Chamber

The freeboard chamber consists of the upper two sections of the combustor. The modules are constructed similarly to the combustion chamber but consist of a 152 cm (60 inch) and 122 cm (48-inch high module with 1935 cm^2 (300 in^2) cross sectional area. The cross sectional area of the freeboard chamber was chosen in anticipation of the largest combustor cross sectional areas to be used. This will reduce particulate carryover due to lower freeboard gas velocities. The modules are carbon steel, mineral wool insulated and refractory lined. The top module is referred to as the exit module and the lower freeboard module as the intermediate module.

With the exception of its large cross-sectional area and its lack of a solids injection port, the intermediate module is identical to the combustor section. This configuration allows for the insertion of freeboard heat exchangers which will be installed to maintain the gas temperatures within the specified limits if a high portion of the combustion takes place in the freeboard due to staged combustion. More importantly, the configuration allows for the installation of staged combustion air ports and sight and sampling ports. Not all openings are effectively usable because of the location of the mezzanine floor and structural steel. The exit module, otherwise similar in construction, has no rectangular access ports for service modules; however, it is equipped with the 15 cm (6 inch) exit ports for the mounting of flue gas ducting or particulate control devices. The top of the module is covered with a refractory-lined lid.

Distributor Plates

To simulate full-scale facilities and to fluidize the bed properly, a distributor plate must have a pressure drop of approximately 30 percent of the bed weight. For this combustor, it is in the range of 0.98 to 3.92 kPa (4 to 16 inches) of water. To allow for the wide variation in operating conditions from 1133 sdm^3/min at 21°C (40 scfm at 70°F) to 7080 sdm^3/min at 427°C (250 scfm at 800°F), six to seven plates are required. This number allows for some overlap, and covers the entire range but does not represent optimum design for all operating conditions in this range. A perforated plate design has been selected for this combustor to accommodate the flow range at an economical cost. The plates are made of stainless steel 310 for temperature and corrosion resistance, reinforced by 0.82 cm (1/8 inch) by 1.27 cm (1/2 inch) flat stock ribs to reduce warpage. The edges of the plates have been slotted to reduce the thermal stresses introduced due to temperature gradients in the plate. The plate when mounted is "floating" in its seal, again reducing internal stresses. Since the plate is only slightly larger than the cross-section of the maximum bed, it will attain a fairly uniform temperature which also helps to minimize distortion.

Heat Exchangers

The combustion zone heat exchangers are bare tube and water-cooled. To accommodate the large turndown requirement, heat exchanger modules can be independently added and removed to attain the cooling requirement for the required mode of operation.

The heat exchangers consist of a plenum, an insulating cover, and hairpin cooling tubes. The tubes and the insulating cover are manufactured from SS 310 and the cooling plenum from low carbon steel. Because a refractory plug would have been too sensitive to cracking, the insulating cover forms the sidewall of the fluidized bed when the heat exchanger is installed. The sidewalls of the cover are made of RA 330 expanded metal to minimize the transfer of energy to the outside wall of the FBC. The cooling tubes may be operated without coolant, particularly during startup when all the energy available should be used to bring the facility up to temperature (up to 871°C (1600°F)). The heat exchangers are vented if no flow is passing through them.

Air Plenum Box

The air plenum box serves as the retainer for the distributor plate, guides the air through the plate and holds the standpipe for the ash removal system. The box is designed so that it can be easily removed. Although blanket insulation is used rather than refractory lining in order to keep the weight of the box down, it is still heavy and requires some support (e.g., a forklift) for servicing. The air pipe connected to the plenum box is mounted on a flexible line and misalignment problems have been minimized. The inner chamber is made of stainless steel 304, and the outside shell is carbon steel.

Bed Height and Temperature Sensors

The bed height is measured via three pressure ports by two differential pressure measurements. One measurement will give the indication of bed density and the other of bed height.

Two temperature probes are provided in the bed and two in the freeboard. Additional thermocouples can be added if desired.

Sampling and View Port

The combustor and the intermediate section both have rectangular openings for the mounting of heat exchangers, sampling, view or injection ports. As described above in the discussion of heat exchangers, view or sampling ports are mounted on carbon steel plates equipped with a cover to form the wall of the bed section or the freeboard. Purge air is provided to keep these ports free of combustion materials.

Injection Ports

Solids injection is accomplished pneumatically. A special entry port has been designed for the inlet pipe to allow the injection of materials close to the distributor plate. If it becomes desirable to change the location of this port, a special injection port could be built to be installed in a heat exchanger slot. The material of construction for the injection tube is stainless steel 310.

A second type of port has been designed and is standard for the staged combustion system with various configurations to satisfy the requirements of tangential and center injection. Very substantial injection velocities can be achieved with these ports if as much as 30 percent of the air is injected at one location by one tube, resulting in very high impinging rates on the opposite side in the combustor. Since these high impinging rates cause local hot spots and wear, it is recommended that the injection rates at any one location be kept low to minimize this problem.

Ash Removal System

The ash removal system consists of a 5 cm (2 inch) diameter pipe that extends through the distributor plate and is held in place by the plenum box. An air operated slide gate valve is operated when the bed height exceeds a preset upper limit initiating a sequence and sounding an alarm of 0 to 5 seconds duration. The valve is opened for 0 to 10 seconds and the actuation is limited to once every 6 to 60 minutes. The ash is discharged into an open container that can accommodate the material from an 8-hour full load test run. The operation of the valve is automatic, with manual override. After the test run, the bin should be emptied to insure the proper operation on the next succeeding test.

2.3 AIR SYSTEM

The air system supplies the fluidized bed combustor with combustion air. In order to burn 10 to 50 kg/hr (22 to 110 lbs/hr) coal as planned, 1133 to 7080 sdm^3/min (40 to 250 scfm) of combustion air is required. The system is capable of heating the air to 427°C (800°F) during startup to preheat the system and ignite the coal. High excess air conditions also require preheated air to maintain combustion temperatures. With flue gas recirculation, up to 25 percent of combustion products may be recirculated.

For staged combustion, the air system is also designed to allow air injection in various locations above the distributor plate.

Figure 2-6 shows the schematic of the air system.

As shown in the flow diagram, air enters the system through a filter/silencer and passes through a throttling valve. This valve is normally open, but can be used to establish a vacuum condition to draw flue gases

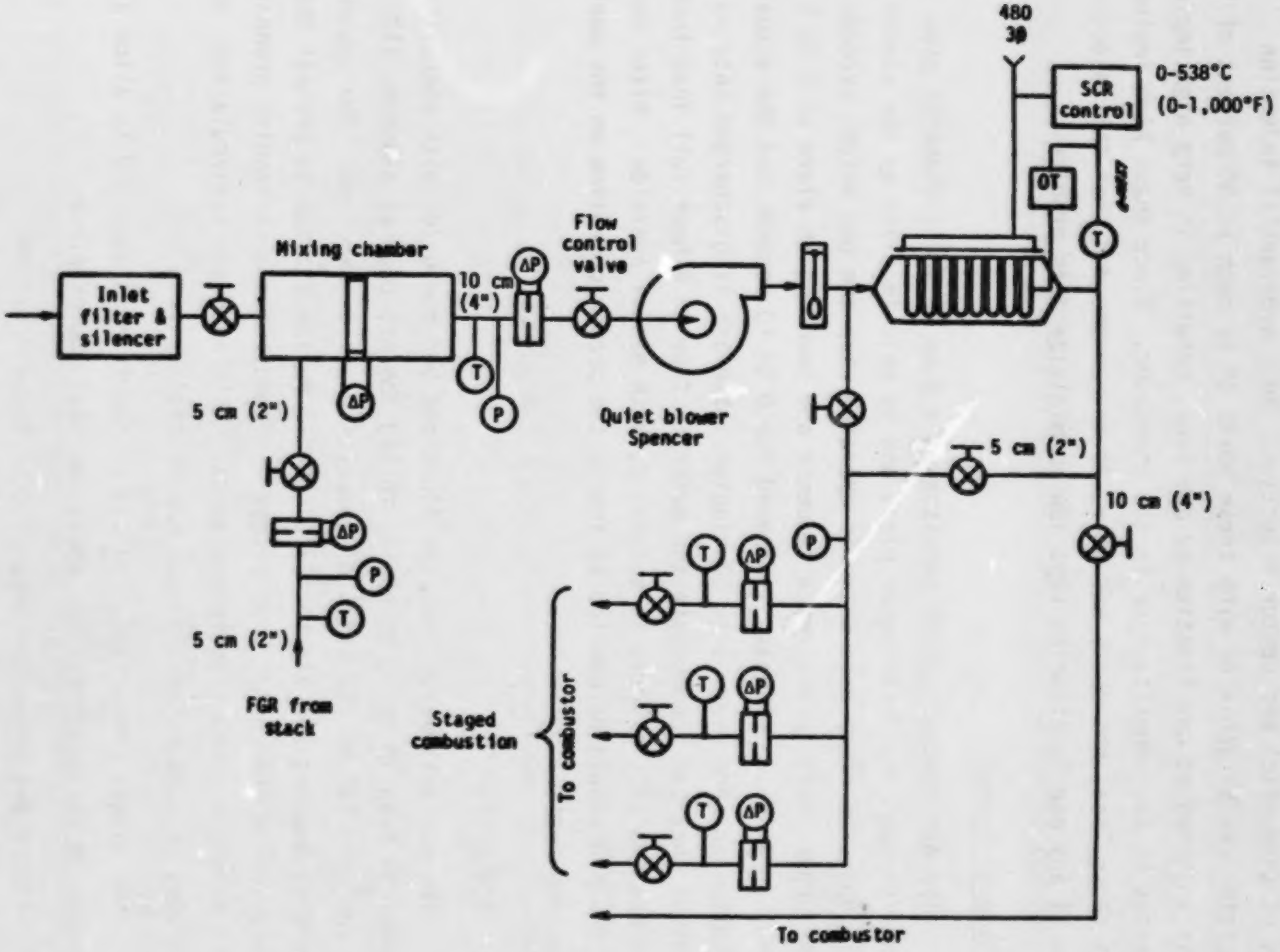
480
3Ø
SCR control
0-538°C
(0-1,000°F)
OT
T
Inlet filter & silencer
Mixing chamber
ΔP
10 cm (4")
T
P
ΔP
Flow control valve
Quiet blower Spencer
5 cm (2")
ΔP
P
T
5 cm (2")
FGR from stack
5 cm (2")
10 cm (4")
P
T
ΔP
T
ΔP
T
ΔP
Staged combustion
To combustor
To combustor

Figure 2-6. Air system schematic.

into the mixing chamber when flue gas recirculation is utilized. The air passes then through the mixing chamber and mist eliminator and is metered for total flow. The inlet valve upstream of the blower is used to regulate the total flowrate. This valve has been placed upstream of the blower to reduce blower surge in low flow conditions. The air is then passed through the blower and the preheater and into the air distribution network. Staged air is metered in each branch.

As the schematic shows, it is possible to draw only flue gases into the blower by closing the throttling valve. This will initiate a fault condition due to overtemperature. Under normal conditions the inlet temperature should not exceed 93°C (200°F). It has been verified that no condensation of SO_x components will occur at the concentrations expected and no damage to the blower will result.

A number of safety interlocks have been provided in the air system. These interlocks are discussed in greater detail in the controls section.

The specifications of the major air system components are as follows:

Control Valves

V-orifice for good flow control at low flowrates

5 cm (2 inch) and 10 cm (4 inch) valves

Blower

Spencer turbine 5010-H

7080 sdm^3/min at 34.5 kPa (250 scfm at 5 psi) pressure, low noise

93°C (200°F) inlet temperature

15-hp motor, 480 V, 30, 60 cycle

Orifices

Maximum pressure drop at rated flow: 2.49 kPa (10 inch) H_2O

Heater

96-kW duct type design

34.5 kPa (5 psi) airtight

SCR control with overtemperature shutoff (815°C (1500°F))

480 V/3Ø

Magnetic contact isolation

The air system utilizes a low-noise Spencer turbine blower, a high reliability device.

2.4 SOLID FEED SYSTEM

2.4.1 Introduction

The solids feed system meets the following requirements:

- Coal feedrate — 10 to 50 kg/hr (22 to 110 lbs/hr)
- Sorbent feedrate — 0 to 22 kg/hr (0 to 50 lbs/hr)
- Ash feedrate — 0 to 10 kg/hr (0 to 22 lbs/hr)
- Air injection flowrate — less than 15 percent (by weight) of total combustion air
- Continuous operation
- Solids particle diameter — 0.63 cm (1/4 inch)
- Pressure at injection point — nominal 117 kPa (17 psia)

The system is shown in Figures 2-7 and 2-8. The major components are:

- Solid feed bins (three) for 8-hour service
- Support frame
- Load cells and readouts on the control console
- Vibratory feeders (3)
- Pressure controlled mixing chamber
- Jet ejector
- Pneumatic transport line
- Service air compressor
- Various gauges and regulators

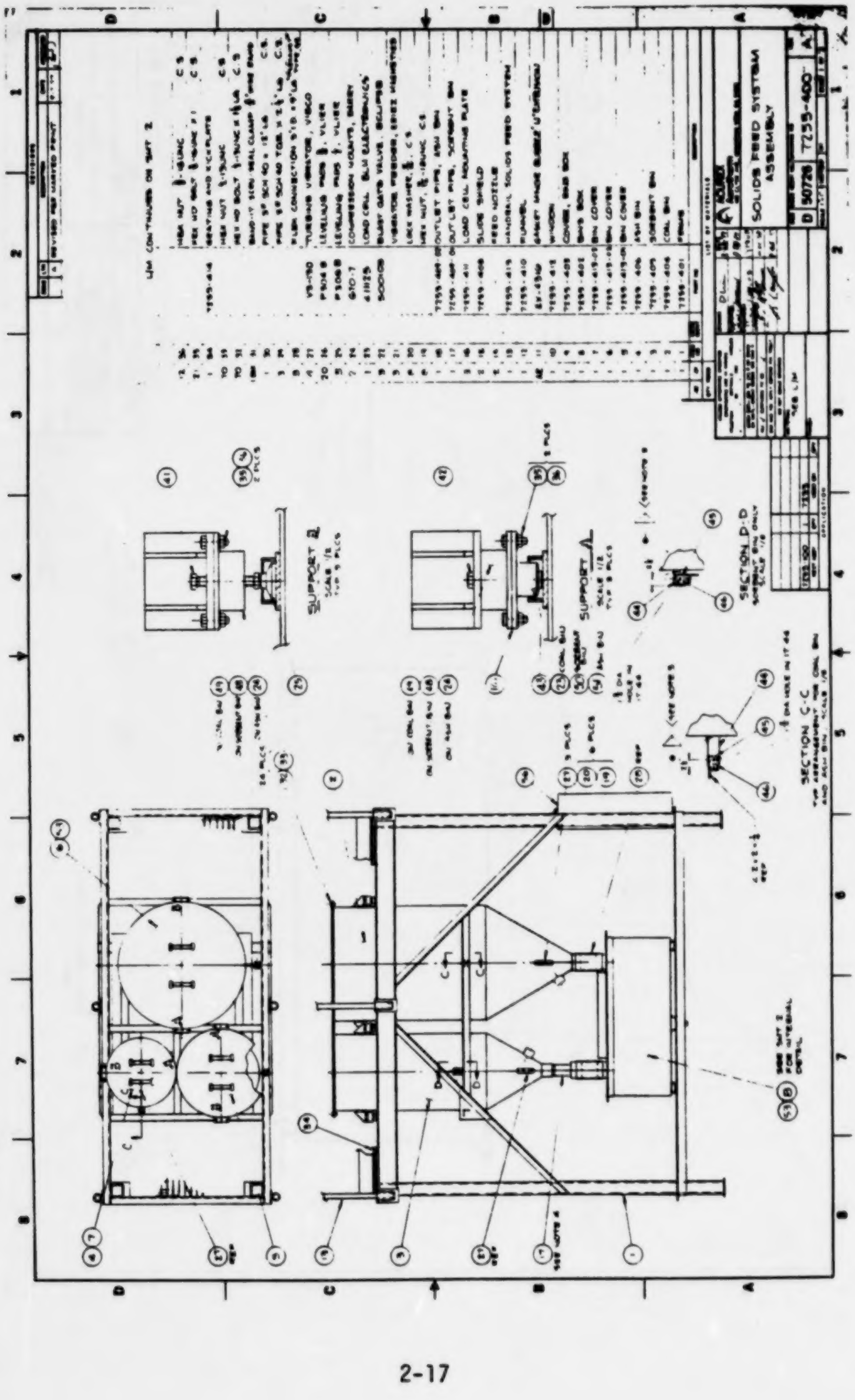
SOLIDS FEED SYSTEM ASSEMBLY
T235-400
SUPPORT A
SUPPORT B
SECTION C-C
SECTION D-D

Figure 2-7. Solids feed system.

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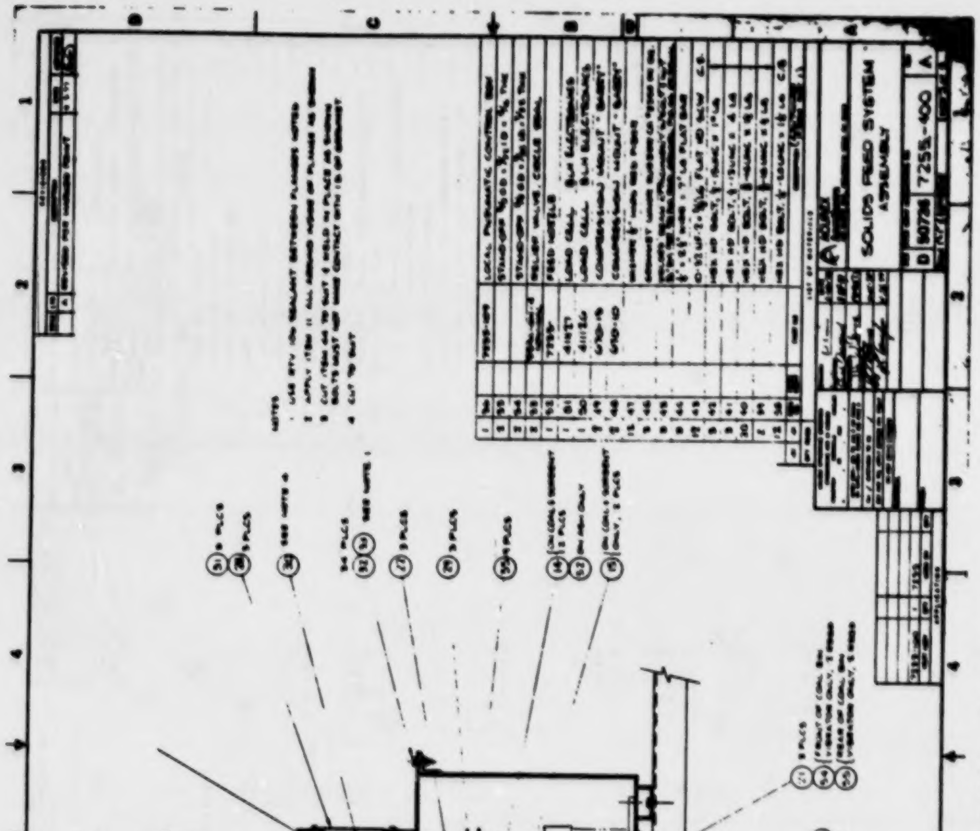
SOLIDS FEED SYSTEM
ASSEMBLY
D 90726 7255-400 A
BINS BOX DETAIL
20 PLCS
8 PLCS
4 PLCS

Figure 2-8. Solids feed system.

Following is a discussion of the injection mechanism methodology.

The coal, sorbent, and flyash is stored in three 8-hour service bins, from which it passes through downspouts onto the base of three vibrating feeders. The feedrate of each feeder can be adjusted at the control console by varying the voltage applied. The mouth of each feeder delivers the materials into a common mixing hopper. The mixing hopper and the vibrating feeders are enclosed in a housing that may be pressurized, if necessary, at high flowrates and pressures. The common hopper guides the materials through a jet ejector that accelerates the particles toward the combustor for injection. A number of gauges, regulators, and valves allows proper adjustment of injection air flowrates.

The bins are supported by load cells that deliver an analog signal to the control console, where a direct readout indicates the respective bin levels. This output can be converted into solids flowrates and gives an accurate indication of mass flowrate. This direct reading method has the advantage of giving accurate results for different materials.

The transport line has been sized to permit flow without saltation over the specified range of solids loading. For a single 2.5 cm (1 inch) inner diameter transport line, using 10 percent of the total combustion gas, it is possible to convey from 16 to 81.5 kg/hr (35 to 180 lbs/hr) of coal/sorbent/ash without saltation (50μ to 0.32 cm (1/8 inch)). Theoretically, at transport velocities greater than the saltation velocity, all solids will be transported. As the transport velocity falls below the saltation velocity, solids begin to drop out of the airstream to roll and slide along the bottom of the transport tube.

In this system, saltation is a problem only if it leads to plugging of the line or excessive pressure fluctuations. If this occurs, a 50 percent increase in transport air flow (or 15 percent of the total combustion gas) will eliminate any saltation in this particle size range. If this alternative proves unattractive, a 1.9 cm (3/4 inch) diameter transport line can be used instead of the 2.5 cm (1 inch) line. This will provide solids flow capability down to 11.3 kg/hr (25 lbs/hr) with 10 percent air flow. Nearly twice the transport velocity, or four times the pressure drop, is required. Maximum transport velocities for the

2.5 cm (1 inch) line would be 30.5 mps (100 fps), using about 906 sdm^3/min (32 scfm) of air.

The solids feed system consists of subsystems accomplishing storage, metering, mixing, and pneumatic transport of coal, sorbent, and flyash to the FBC. Controls and instrumentation are included to assure constant flow and easy regulation of solids feedrate and air flow to the combustor.

Detailed descriptions of the individual components are given in the following subsections.

2.4.2 Storage Bins

Each bin has been sized to allow more than 8 hours supply of material at maximum feedrate.

The 60° cone-bottom, cylindrical bins are each suspended at two points just below the top flange. One of the supports is a radiused load-cell, and the other (on the opposite side of the bin) is a Vlier pivot mount. Horizontal constraint is provided by a rubber restraining grommet located below and at 90° to the pivot line.

Each bin is sealed to a common "mixing box" below by a 7.6 cm (3 inch) rubber sleeve. Each bin is also sealed at the top with a gasketed lid.

An adjustable feed nozzle at the outlet of each bin provides cross-flow regulation. Adjustment of these nozzles is addressed in Section 3.

2.4.3 Feeders

The solids feedrates are individually controlled with three specially modified Eriez Model 15A vibratory feeders. By regulating the input voltage of each feeder (through individual auto transformers), the vibration amplitude of each feeder tray is controlled, and hence, the feedrate of each solid.

Each feeder has been modified to prevent particle size segregation due to vibration, and to control the amount of solids on the tray (which is important for uniformity of flow). Because of differences in particle size distribution, and other dust characteristics (density, sphericity, etc.), the flyash feeder requires a slightly different tray design than the coal and sorbent feeders.

2.4.4 Loadcells

BLH Electronics Type C2M1 strain gage loadcells are used as the primary measurement of individual solids feedrate. Each bin is supported (on one side only) by a loadcell of the appropriate range, a 900 kg (2000 lb) model for the coal bin, a 450 kg (1000 lb) model for the sorbent bin, and a 225 kg (500 lb) model for the flyash bin.

As mentioned, each loadcell supports only half the total bin weight. But, because each loadcell circuit has a span adjustment, each has been adjusted to read actual total weight (in lbs.). Also, through an adjustable zero level, the weight of an empty bin can be set to be zero (or some other convenient number if zero is out of range).

There are several possible sources of error in the loadcell reading that can be avoided through proper action. Because only one loadcell is used, it is important to load the bin evenly to distribute the weight equally. Secondly, the loadcell reading has a slight dependence on bin pressure, hence, a change in air flow can affect weight readings if constant bin pressure is not maintained. These and other possible sources of error in weight readings are discussed further in Section 3.

2.4.5 Vibrators

To assure smooth and continuous flow of solids to the feeder (especially at low bin levels), and to prevent "ratholes and bridges" in each of the materials, it is necessary to provide external agitation. For this purpose, the bins are equipped with Vibco Model VS-130 turbine vibrators. Both the coal and sorbent are fairly easy to handle solids and therefore need only one vibrator each. The vibrator is located on the cone section of the bin and is used primarily at near-empty conditions.

The flyash, however, being less dense, smaller, and stickier has a vibrator mounted on the outlet downcomer in addition to one on the cone.

Controls exist to vary the inlet pressure to all vibrators and to vary the duty cycle of each vibrator. They are discussed in the controls section.

2.4.6 Pressure Relief

The solids feed system comes equipped with two, redundant Circle-seal model 559 pressure relief valves.

Without pressure relief, if the transport tube clogged, the bin would be quickly pressurized to the ejector supply pressure — as high as 689 kPa (100 psi). Obviously, the bins and mixing box are not designed to withstand this pressure. The relief valves will insure that the bin pressure does not exceed a preset level.

For adjustment instructions, see Section 3 and the manufacturer's instructions.

2.5 GAS CLEANUP SYSTEM

The gas cleanup system can be divided into two categories: high-temperature devices and low-temperature devices. The high-temperature devices are the primary and secondary (or "tornado") cyclones (540°C to 1080°C) (1000°F to 2000°F). The low-temperature devices are the electrostatic precipitator (ESP) and the baghouse (149°C to 260°C) (300°F to 500°F). Each of these is discussed in further detail in the following subsections.

Other kinds of cleanup devices can easily be evaluated by rerouting the ducting or bolting the devices in place of the installed equipment. The low-temperature systems can be particularly easily adapted with flexible hoses.

2.5.1 Primary Cyclones

Experience with FBC units has shown that a small portion (∿10 percent) of the coal carbon is not combusted during the first combustion cycle. These unburned materials are usually collected in vertical separators or cyclones and recycled to the combustor or fed into special burnup cells for combustion.

The primary cyclone collector has been designed to have a cut size of 7μ at the typical operating condition of 18,400 adm^3/min (650 acfm).

Since this facility will be used over a wide range of operating conditions, some of the components have been oversized. This is particularly true of the blower. A higher than normal pressure drop in the cyclone can thereby be tolerated. Higher pressure drops or velocities through a cyclone also imply smaller cut sizes — a desirable feature. The cyclone has, therefore, been slightly undersized for the design point, in order to allow collection of materials at low flowrates. Higher pressure drops (to a maximum pressure drop of 2.49 kPa (10 inches H_2O) at higher operating flowrates must be accepted. The cyclone must also operate at elevated temperatures.

Two methods of construction were considered for the primary cyclone: (1) Hastelloy X lined construction with high-temperature insulation on the outside, and (2) refractory-lined construction of carbon steel. The refractory-lined carbon steel shell construction was selected because refractory is not as sensitive to corrosion or limited to a maximum operating condition of 1080°C (2000°F). Some pilot scale facilities have also experienced fires in the cyclones during upset conditions and this was considered in the design.

2.5.2 Tornado Cyclone

For the collection of particles not captured by the primary cyclone, a tornado-type cyclone is provided and placed in series with and immediately downstream of the primary cyclone. Gas flow from the primary cyclone can be directed through the tornado device.

The unit installed is an Aerodyne Model 400SV dust collector. It is reported to have greater collection efficiencies for small particles than conventionally designed cyclones due to the increased vorticity within the cyclone body. This added swirl results from the provision of a secondary airstream directed in such a way as to increase the tangential velocity of the flow within the cyclone body.

The unit is constructed from SS 310 and is externally insulated with a ceramic fiber felt for heat retention and personnel safety. For this unit to operate properly, the pressure drop between the secondary inlet and outlet duct must be adjusted by dampers during operation. The pressure drop must be on the order of 30.5 kPa (12 inches H_2O). At this pressure drop, the flowrate in the secondary leg is 7530 adm^3/min (266 acfm). The primary flow can then be adjusted to make up for the difference in flow, to a maximum of 11,330 adm^3/min (400 acfm). A portion of the flow may be bypassed should the capacity of the unit be exceeded.

2.5.3 Electrostatic Precipitator

The combustion gases are initially cleaned by the two inertial collectors immediately downstream of the FBC. The gas is then cooled, in order to allow for the use of commercially available electrostatic precipitators (ESP) and fabric filters (baghouse). Several full-scale industrial ESP's have been operated at temperatures of about 427°C (800°F). Temperature limits for fabric filters, however, are established by the temperature limits of the filter materials now available. Teflon, fiberglass, and Nomex are recognized to be state-of-the-art high-temperature filter materials. Their maximum allowable temperature limit is in the range of 232°C to 260°C (450°F to 500°F). In order to provide a cost-effective solution to the need for evaluating both ESP and filter technology, the gas will be cooled to approximately 260°C (500°F) by using the flue gas heat exchanger.

Full-scale industrial electrostatic precipitators are of the single-stage design. A two-stage design was, however, the only design available in the size required for this project (11,300 adm^3/min at 260°C) (400 acfm at 500°F). The design point represents the nominal midpoint in the flow range for the FBC. This value has also been used in the selection of the baghouse. On the average, efficiency will increase for lower flow and will decrease for higher flow values.

ESP's in the 11,330 to 14,200 adm^3/min (400 to 500 acfm) size range are typically designed for cleaning air circulating through heating and air-conditioning systems or for cleaning the effluent from grease cookers. Due to cost, weight and ease of fabrication, aluminum is generally used in constructing ESP's of this kind. Aluminum, however, is not acceptable for the 260°C (500°F) inlet condition specified above. Therefore, a special design using 304 SS was selected for this project. The unit was fabricated by Beltran Associates using their standard design dimensions for a 11,330 adm^3/min (400 acfm) unit. The unit consumes less than 100 watts of power and collects 70 to 95 percent of the particles that are not collected by the upstream collectors. (Ninety percent of the particle sizes passing through these inertial devices are predicted to be less than 2 μm; achieving high overall collection efficiencies is made difficult by these smaller particles.)

2.5.4 Baghouse

In order to evaluate the compatibility of available fabric filtration technology with the combustion products generated by an FBC, a fabric filter (baghouse) was installed in series with the ESP. Although the inlet grain loading and the mass median diameter of incoming particles is significantly reduced (approximately 0.023 gm/fm^3 (0.01 grains/scf) and 0.8 to 0.9 μm), the provision of this unit allows for the evaluation of filtration devices on FBC effluents.

Commercially available baghouses in the 11,330 adm^3/min (400 acfm) range offer any of the following techniques for cleaning the accumulated dust cake from the filter surface:

- Reverse flow
- Mechanical shake
- Reverse pulse

Multiple units would be required for either of the first two mechanisms due to the need for removing the filter from the process during fabric cleanup. Moreover, the gradually increasing pressure drop followed by a sudden drop (as one unit is taken off stream and another is put back online) is undesirable for the air system being designed.

The reverse pulse technique of fabric cleaning is not burdened with either of these limitations. The reverse pulsing technique is accomplished by rapidly pulsing (∿0.1 sec) the tubular bags with compressed air. The shock wave, as it travels the length of the filter, dislodges the accumulated dust cake. The interval between pulsing is usually determined by the inlet grain loading, and is preprogrammed so that the pulsing of various bags is continuous.

A reverse pulse unit with a virtually static pressure differential has been procured for this program. The unit is a Young Industries vertical/modular "UniCage" filter collector, Model Number VM 42-16. The design of this unit allows for the easy replacement of the filter tubes for the evaluation of various high-temperature fabrics. The VM 42-16 is constructed of carbon steel and contains 6.78 m^2 (73 square feet) of teflon felt. The unit requires 57 sdm^3/min (2 scfm) of dry, oil-free air at 620 kPa (90 psig) for the reverse pulse cleaning.

2.6 FLUE GAS HEAT EXCHANGERS AND SOOT BLOWING LANCE

The flue gas heat exchanger cools the high-temperature exhaust gases from up to 1094°C (2000°F) to approximately 204°C (400°F). At this temperature, no condensation will occur in the ESP or baghouse. Thus, severe corrosion will be avoided. The flowrate is 1133 to 7080 sdm^3/min (40 to 250 scfm) and the heat transfer requirement is 42,400 kJ (40,000 Btu/hr) to 594,000 kJ (560,000 Btu/hr).

The heat exchanger installed (Figure 2-9) consists of a refractory-lined carbon steel shell. Ten bare tube heat exchangers provide the large turndown required. During operation, only those units required for cooling are turned on. All other units are connected to a drain. The tubes themselves are made out of 1.6 cm (5/8-inch) outer diameter SS 304 tubing mounted in carbon steel plenums.

Experience with the heat exchangers in multifuel furnaces has shown that considerable solid material can collect on the tubes. This calls for wider spacing of the first heat exchanger tubes than of the later tubes. To clean the tubes without requiring the removal of the heat exchangers, a soot blowing lance (Figure 2-10) has been provided. The lance can be used to clean the tubes while the unit is in operation. Entry ports for the probe have also been provided. Through these, the probe can be inserted and an air spray jet be directed onto the tubes. The soot material falls to the bottom of the heat exchanger, where it is collected in an ash drawer that can be easily removed and emptied.

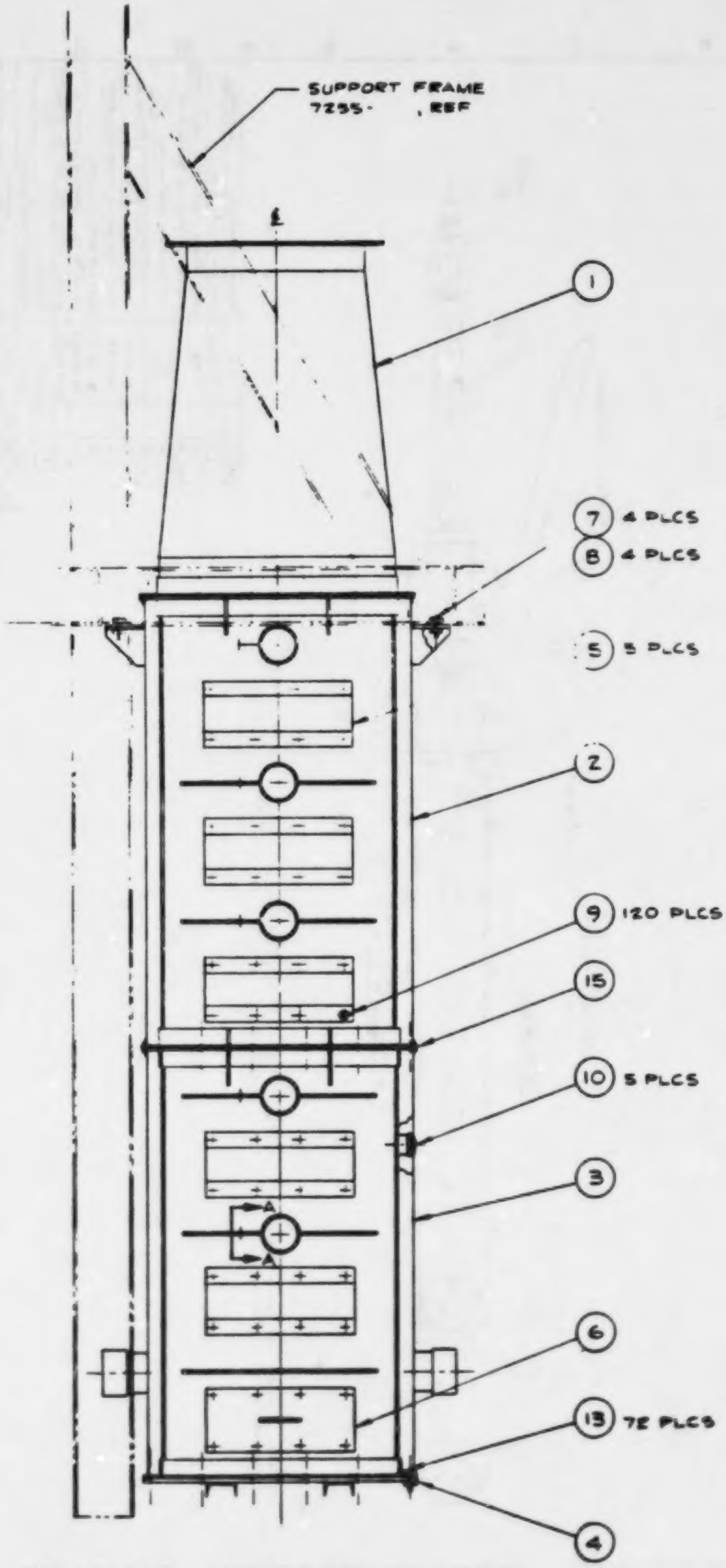
SUPPORT FRAME
7255- , REF
℄
①
⑦ 4 PLCS
⑧ 4 PLCS
⑤ 5 PLCS
②
⑨ 120 PLCS
⑮
⑩ 5 PLCS
③
A
A
⑥
⑬ 72 PLCS
④

Figure 2-9. Flue gas heat exchanger.

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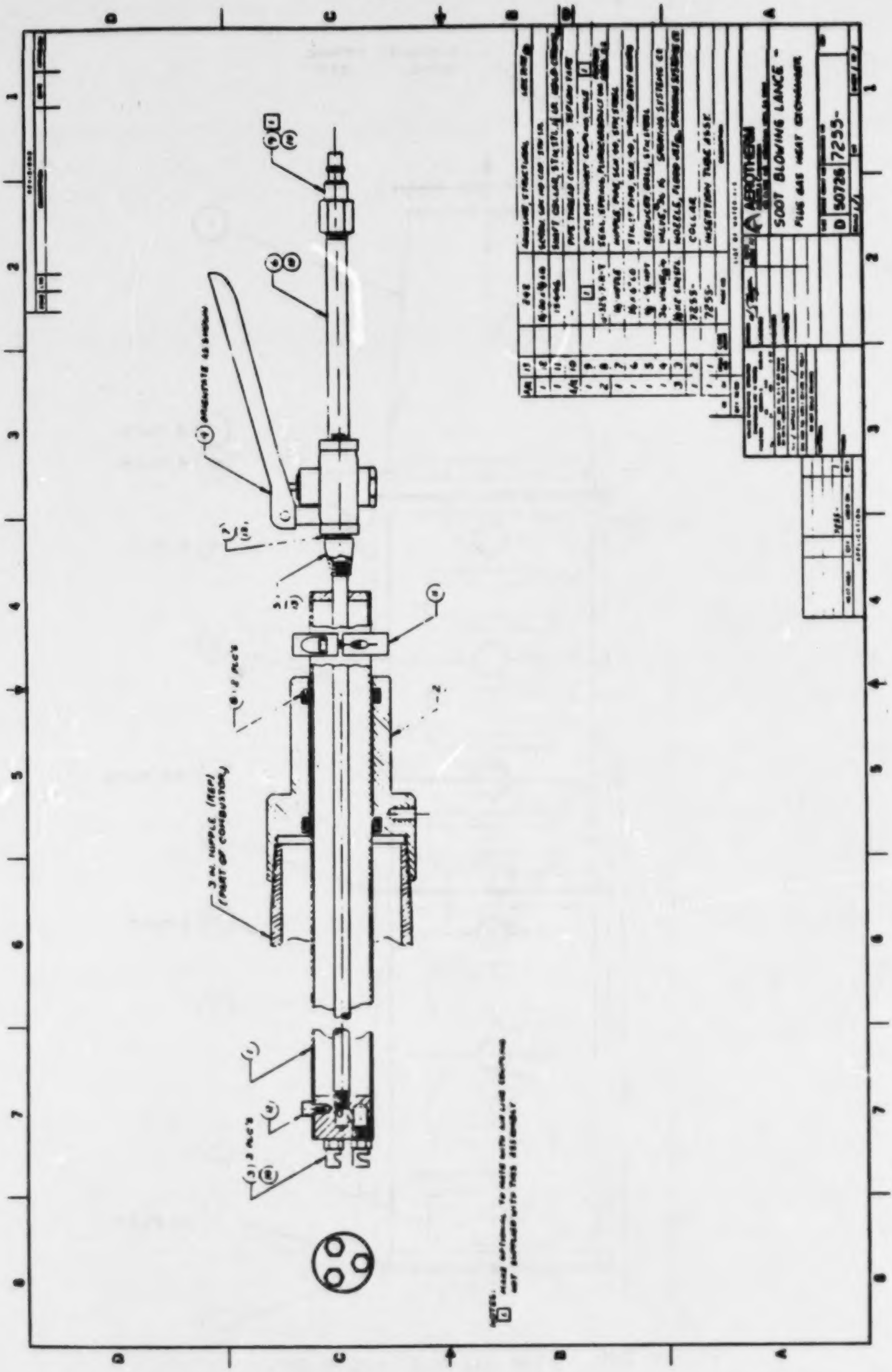
SOOT BLOWING LANCE -
FLUE GAS HEAT EXCHANGER
AEROTHERM
D
50726
7255-
COLLAR
INSERTION TUBE ASSY.
3 IN. NIPPLE (REF)
(PART OF COMBUSTOR)
ORIENTATE AS SHOWN
NOTES:

Figure 2-10. Soot blowing lance.

2.7 CONTROL SYSTEM

2.7.1 Introduction

The controls and instrumentation of the FBC test rig serve four basic subsystems:

- Fluidization air supply system
- Coal/sorbent storage and transport system
- Fluidized-bed combustion unit
- Flue gas cleanup system

Each of these subsystems has distinct measurement capabilities which are equipped with special alarms or interlocks. These alarm systems have adjustable set-points and are interlocked with the process safety and interlock system.

Three of the above systems are essentially always used in a similar configuration and represent the heart of the FBC. The flue gas cleanup system, however, will be arranged into many different configurations to suit the needs of the test. These devices are also relatively passive and require little control. The philosophy followed here is to provide "plug in" capability to measure the desired temperatures and pressures, and to provide the required alarm capability.

Fluidization Air Supply System

The fluidization air input to the combustor is controlled by separately controlling the total air flowrate and the flue gas recirculation (FGR) rate. Each of these is controlled by the operation of manual valves. The total fluidization air flowrate and the FGR flowrate are derived by measuring the differential pressure across orifices. The absolute pressure and temperature are measured for mass flowrate computations. The amount of excess air is measured indirectly by measuring the oxygen content in the flue gas. The excess air is controlled by adjusting the ratio of ambient air to flue gas.

Coal/Sorbent Storage and Transport System

The coal, sorbent, and ash feedrates are controlled by manually adjusting a variac controller on the control console. The voltage variation in turn causes a more or less severe vibration of the vibratory feeders. Direct-reading mass transducers give indications of the various amounts of materials being fed into the FBC.

When coal, sorbent, or ash is fed, the pneumatic transport air is controlled by manual valves and measured by means of a laminar flow element in the line. As before, absolute pressure and temperature are measured for mass flowrate computations.

Each supply bin is equipped with a status alarm to indicate a low supply. Because of the abrasive nature of coal, erosion of pneumatic transport lines can cause problems. These have been minimized by design.

Fluidized-Bed Combustion Unit

Temperature in the fluidized bed combustion unit is measured at multiple locations within the bed and the freeboard. Although any one of the temperatures could be controlled, only bed temperature is controlled. This is done by controlling the water flowrate in the cooling coils and by adding or removing heat exchanger surface area. Cooling water flowrate and inlet/outlet temperatures are measured for energy balance computations. The bed height can be controlled by installing an overflow port at the appropriate location. Ash can be removed automatically through the removal tube to maintain the bed height within a certain height tolerance band. Bed height is measured by noting the pressure differential between three known points — two in the bed region and one in the freeboard. In the same way, bed density is measured by reading the pressure differential between two points a known distance apart within the bed, and the bed height in proportion to a third point. Other pressures measured are inlet pressure, freeboard pressure, and distributor pressure differential.

Safety interlocks include low air velocity, bed overtemperature and heat exchanger overtemperature.

Flue Gas Cleanup System

For each cleanup device, three measurements are made;

- Pressure differential inlet/outlet
- Inlet pressure
- Inlet temperature

Of these, only the first inlet temperature after the chiller is controllable. This control is achieved by adjusting the water flowrate in one or more of the chiller banks, using manual valves. The inlet and outlet bulk temperatures on each bank are measured. To provide the required flexibility, outlet boxes for the measurement umbilicals are provided near these devices. This allows the setup in any required configuration.

Safety interlocks include a cleanup device inlet overtemperature warning light and a high differential pressure warning. Figure 2-11 shows the system P&ID.

2.7.2 Control Systems – Panels

The control system is divided into four major sections corresponding to the functional systems (see Figure 2-12).

- Air supply system instrumentation
- Coal/sorbent storage and transport system instrumentation
- Fluidized-bed combustion unit instrumentation
- Flue gas cleanup system instrumentation

The controls and meters are on standard 48.2 cm (19 inch) panels mounted in vertical twin rack assemblies which are bolted together. Each panel is assigned to a specific subsystem, thus simplifying console operation and providing minimum disruption if maintenance or modification is required on a given subsystem.

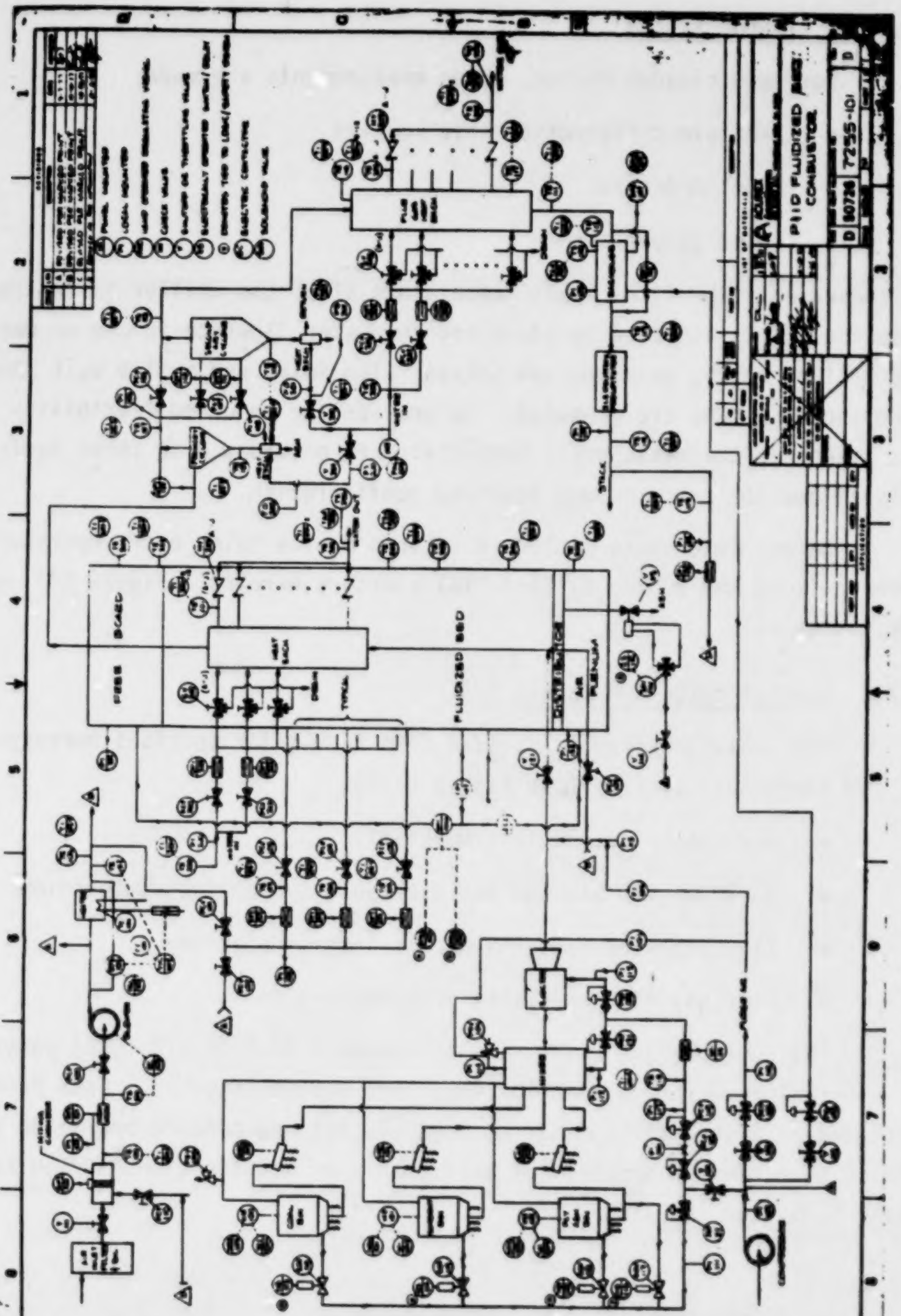
P110 FLUIDIZED BED COMBUSTOR
7255-101
FLUIDIZED BED
AIR PLENUM
FREE BOARD
STACK
TYPICAL

Figure 2-11. P&ID.

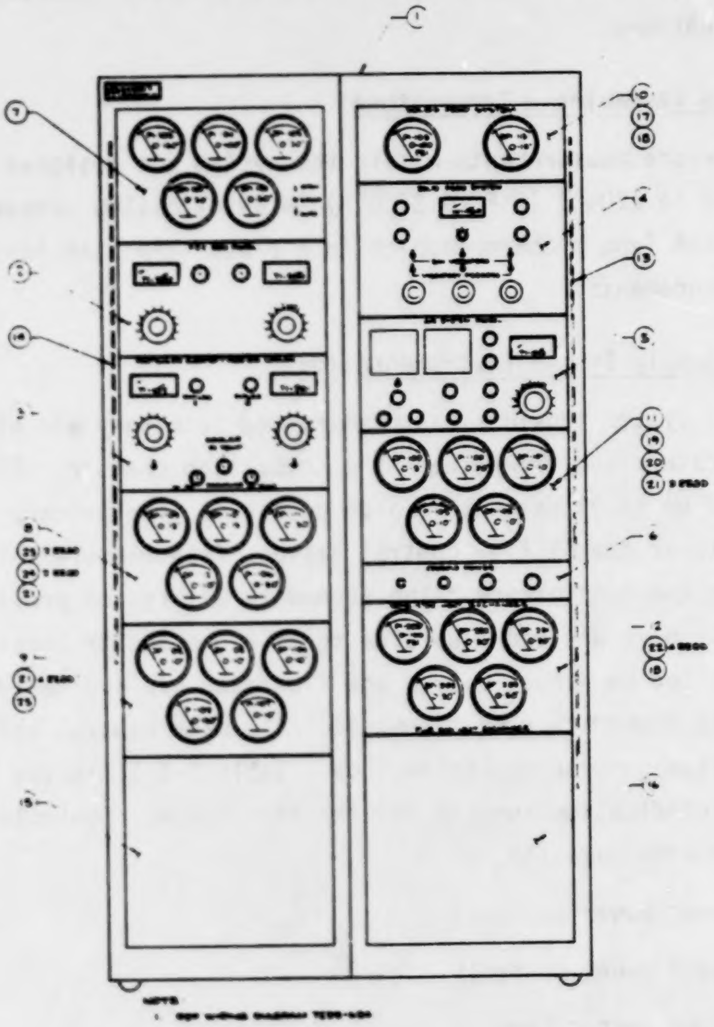
1
7
10
17
18
4
13
14
5
11
19
20
21
6
8
23
24
2
22
9
16
NOTE:

Figure 2-12. Control console.

Measurement Methods

Process Variables — Pressure

Pressure measurements in all areas of the FBC are made using magnehelic pressure gauges. These gauges have proven their accuracy and economy in many applications.

Process Variables — Temperature

Temperature measurements within the system are designed to be within the range of 0 to 1204°C (0°F to 2200°F) in an oxidizing atmosphere. Acurex has selected ISA Type K thermocouples in a closed tip stainless steel sheath for these measurements.

2.7.2.1 Air Supply System Instrumentation

The air system provides the primary and secondary air at a controlled temperature and flowrate to the combustion chamber. Flue gas recirculation of up to 25 percent is also possible. The primary air supply system consists of manual flow control valves, flow measurement devices, the blower, heater and controllers. The secondary air system provides air for staged combustion at desired flowrates to three combustor locations. The flow is controlled by manual valves and flowrates are indicated indirectly by pressure and temperature measurements. The same control philosophy applies to the flue gas recirculation loop. Table 2-1 lists the measurements, ranges and identification numbers for the air system. Controls located on the air system panel are the:

- Blower power controls
- Heater power controls
- Heater controllers
- Temperature sensing selector switch and
- Heater lights for the blower, heater, blower inlet temperature, heater overtemperature and air flowrate.

Two temperature controllers are provided to control the air preheat temperature and protect the heater from sheath overtemperature. The heater was

TABLE 2-1. AIR SUPPLY SYSTEM INSTRUMENTATION

Measurement	Range	P&ID Identification 7255-101D	P&ID Loc. 7255-101D
FGR & air mixing screen diff. pr.	0-1.25 kPa (0.5" H_2O)	DPI-100	D-7
Main orifice inlet pr.	0-5 kPa (0-20" H_2O)	PI-100	D-7
Main orifice diff. pr.	0-2.5 kPa (0-10" H_2O)	DPI-101	D-7
Main orifice inlet temp.	0-93°C (0-200°F)	TE-100/TI-100-1	D-7
Blower trip temp.	93°C (200°F)		
FGR inlet pressure	0-2.5 kPa (0-10" H_2O)	PI-105	A-4
FGR orifice diff. pr.	0-2.5 kPa (0-10" H_2O)	DPI-108	A-4
FGR inlet temperature	0-316°C (32°F-600°F)	TE-115/TI-100-2	A-3
Low air velocity switch	0-0.125 kPa (0-0.5" H_2O)	DPS-100	D-6
Air heater sheath temp.	0-871°C (0-1600°F)	TE-101/TY-101	D-6
Air heater outlet temp.	0-649°C (0-1200°F)	TE-102/TIC-102	D-6
Secondary air inlet pr.	0-37.3 kPa (0-150" H_2O)	PI-102	C-6
Secondary air LEG I orifice diff. pressure	0-25 kPa (0-10" H_2O)	DPI-102	C-6
Secondary air LEG I inlet temperature	38-538°C (100-1000°F)	TE-103/TI-102-2	C-6
Secondary air LEG II orifice diff. pressure	0-2.5 kPa (0-10" H_2O)	DPI-103	C-6
Secondary air LEG II inlet temperature	38-538°C (100-1000°F)	TE-104/TI-102-3	C-6
Secondary air LEG III orifice diff. pressure	0-2.5 kPa (0-10" H_2O)	DPI-104	C-6
Secondary air LEG III inlet temperature	38-538°C (100-1000°F)	TE-105/TI-102-4	C-6

designed to deliver up to 427°C (800°F) air to the combustor. This requirement dictates slightly higher temperatures at the heater outlet of approximately 454°C (850°F). The sheath temperature must not exceed 871°C (1600°F) and in order to insure that this does not occur, should be controlled to a maximum of 815°C (1500°F) at the sensing location. Tests have verified that 538°C (1000°F) heater outlet temperatures are safely achievable.

2.7.2.2 Solids Feed System Instrumentation

The solids feed system controls are divided into two sections. All pneumatic controls are located on the solids feed frame control panel, whereas electrical controls and interlocks are located on the main control panel. Figure 2-13 clearly identifies those controls located on the solids feed system and those located on the main control console.

There are two panels on the main control console used in controlling and monitoring the air and solids flow (Figure 2-14).

The air flowmeter panel is located at the top right of the console. It shows air flowmeter inlet pressure and differential pressure across the flowmeter.

The solids control panel is located on the lower right side. It provides the following functions:

- Feeder controls — on/off control only
- Bin weight monitors — load cell readout and selector switch
- Low bin level indicator lights

Ejector

It is advantageous, for two reasons, to be able to control the air flowrate and bin pressure independently. First, it allows continuous load-cell readings while varying air flowrate. Secondly, the bins can be loaded without stopping the airflow (by depressurizing the bins). Normally (with a plain transport line), the bin pressure will vary with the square of the air flowrate, and will also vary directly with the combustor inlet pressure.

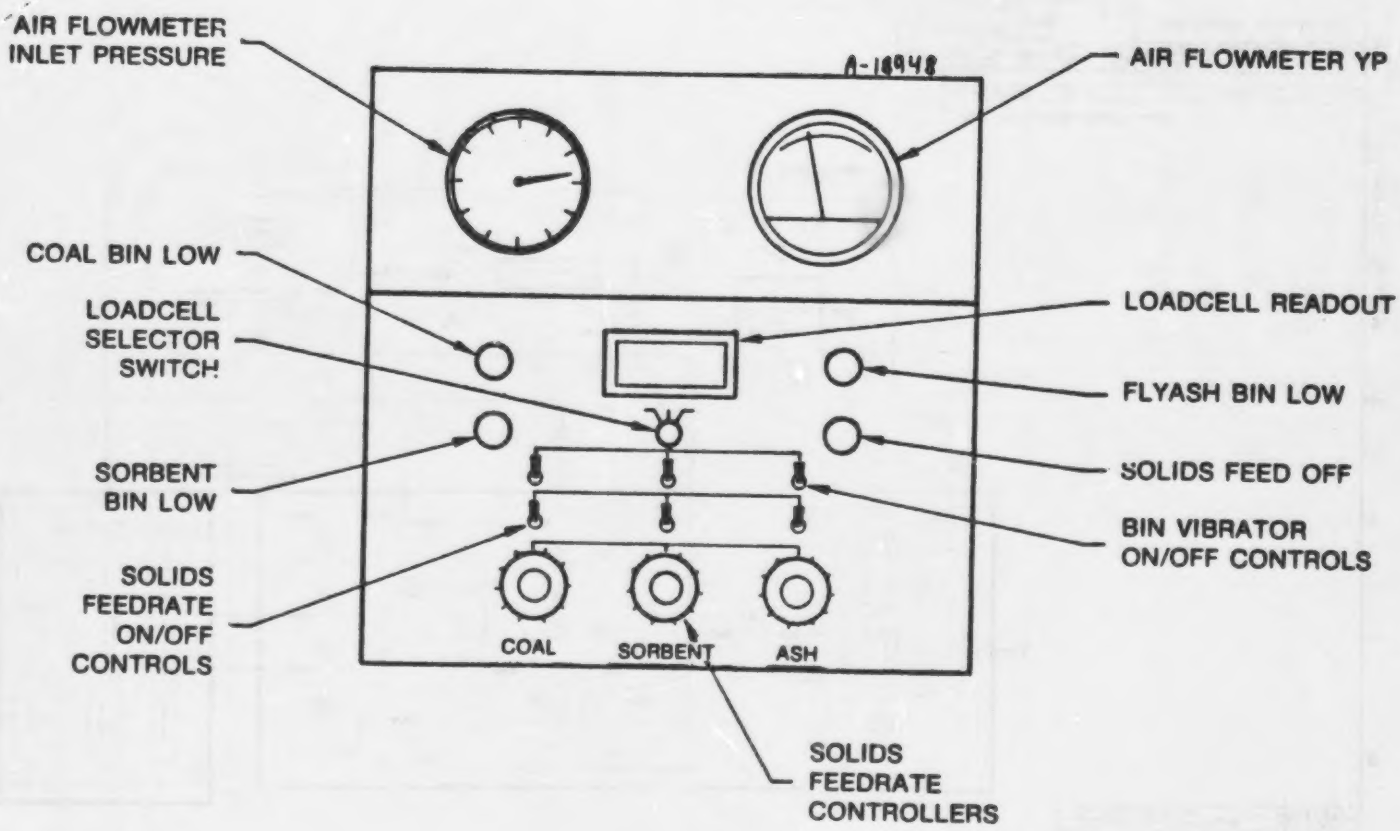
AIR FLOWMETER INLET PRESSURE
A-18948
AIR FLOWMETER YP
COAL BIN LOW
LOADCELL SELECTOR SWITCH
SORBENT BIN LOW
SOLIDS FEEDRATE ON/OFF CONTROLS
LOADCELL READOUT
FLYASH BIN LOW
SOLIDS FEED OFF
BIN VIBRATOR ON/OFF CONTROLS
COAL
SORBENT
ASH
SOLIDS FEEDRATE CONTROLLERS

Figure 2-13. Main control console -- solids feed system panels.

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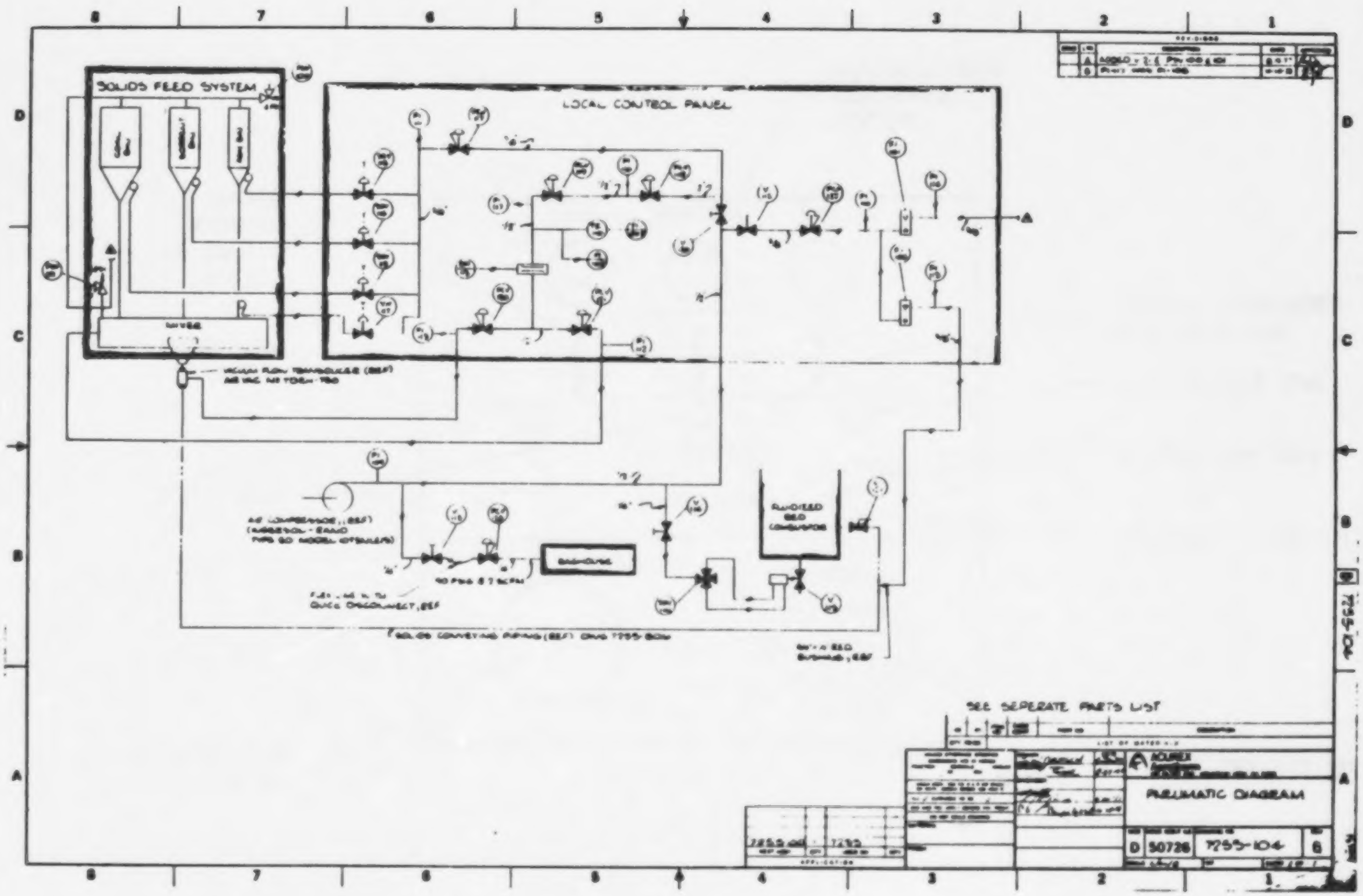

SOLIDS FEED SYSTEM
LOCAL CONTROL PANEL
MIXER
FLUIDIZED BED COMBUSTOR
SEE SEPERATE PARTS LIST
PNEUMATIC DIAGRAM
D
50726
7255-104
B
7255-104
A
B
C
D
1
2
3
4
5
6
7
8

Figure 2-14. Pneumatic diagram.

By adding an Air-Vac engineering Model TORH-750 air ejector to the transport line, the air flowrate and bin pressure are decoupled. This can be seen by noting that the air flow can be made up of virtually any combination of inlet air and supply air (as shown in Figure 2-15), and by noting that as the supply air increases, so does the pressure rise across the ejector. Figure 2-16 shows the map of values that the ejector can cover in this system.

Local Control Panel

The local control console is located at the right edge of the solids feed system structure. It is mounted on a swivel to permit viewing and access from either the main control console or from the front of the solids feed system.

The local pneumatic control panel, shown in Figure 2-17, provides nearly all of the control and instrumentation to regulate and monitor the air flow, bin pressure, and vibrator pressure. FBC inlet pressure is also provided on the local control console.

Operation and specific function descriptions are contained in Section 3. Table 2-2 identifies all measurements, identification and locations for the solids feed system.

2.7.2.3 Fluidized Bed Combustion Unit Instrumentation

The active control subsystems in the FBC test rig are the air system and the solids feed system. Although the combustion actually takes place in the combustor, it is otherwise a rather passive element. The instrumentation associated with the combustor consists primarily of overtemperature protection devices and temperature and pressure measurement devices. Temperature alarms alert the operator and simultaneously shut down the solids feed. Measurements are listed in Table 2-3. The temperature in the bed is primarily controlled by the amount of heat exchanger surface submerged in the bed and secondarily by the water flowrate. The water flowrate control can only achieve a 2:1 heat transfer turndown and is therefore not viable for temperature control. The temperature is primarily controlled through excess air and coal feed rates.

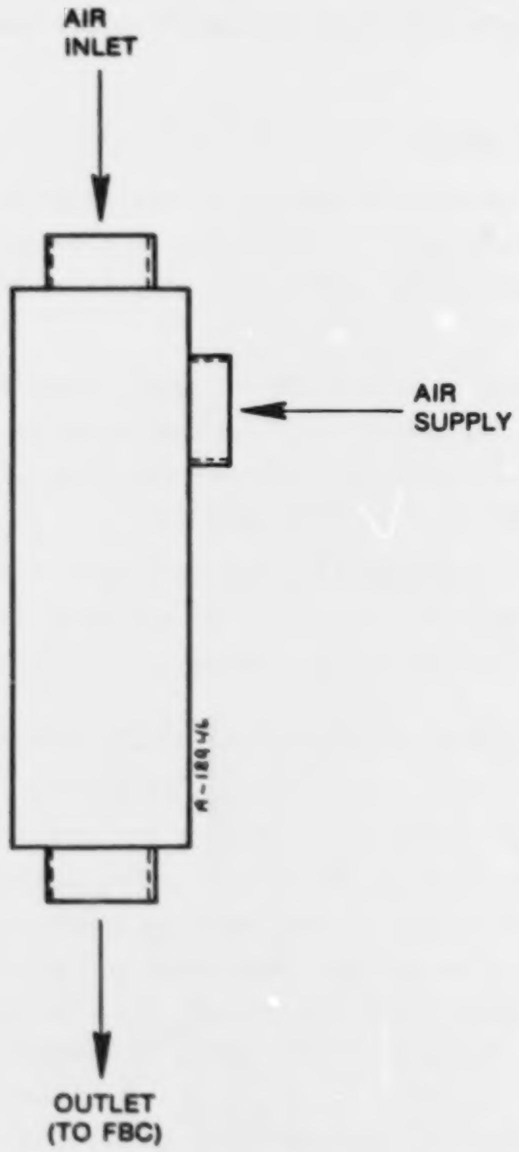

AIR INLET
AIR SUPPLY
A-18946
OUTLET (TO FBC)

Figure 2-15. Air ejector nomenclature.

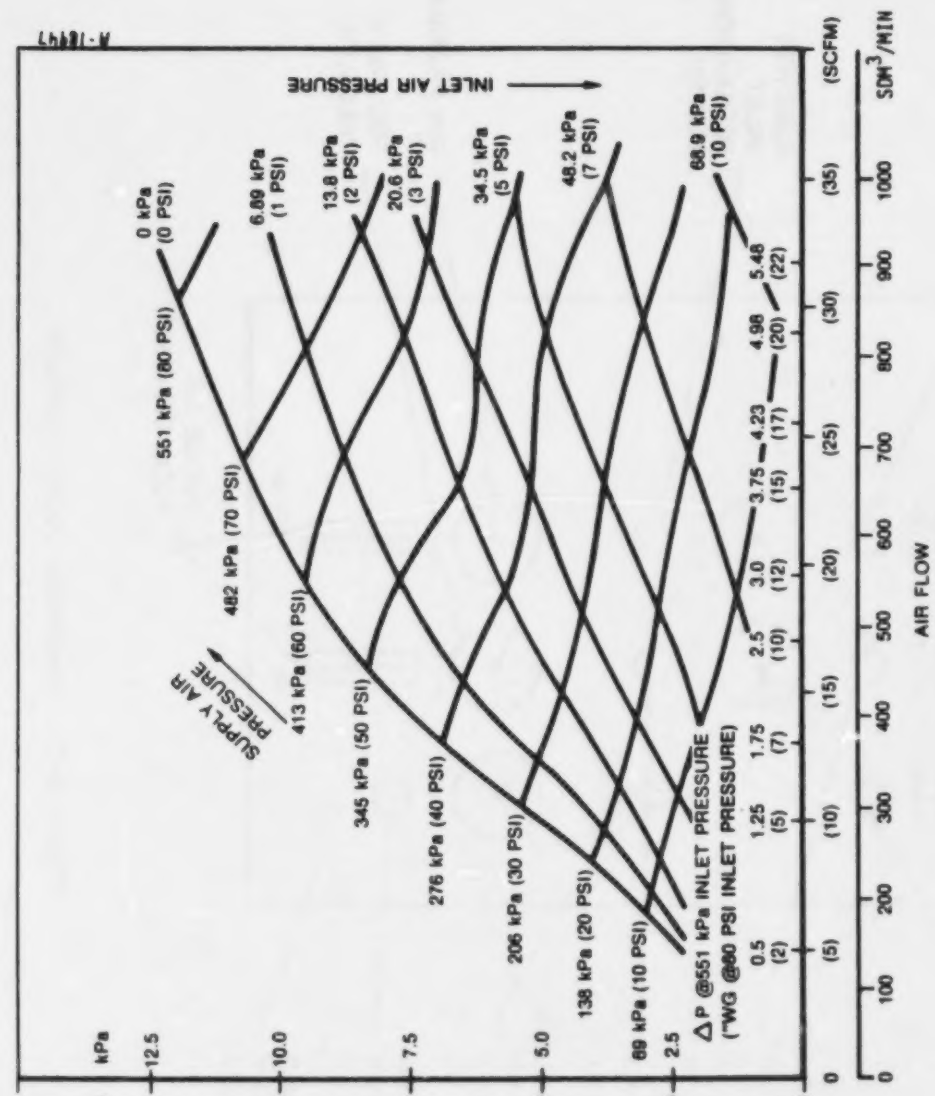


Figure 2-16. Ejector pressure rise vs. air flow.

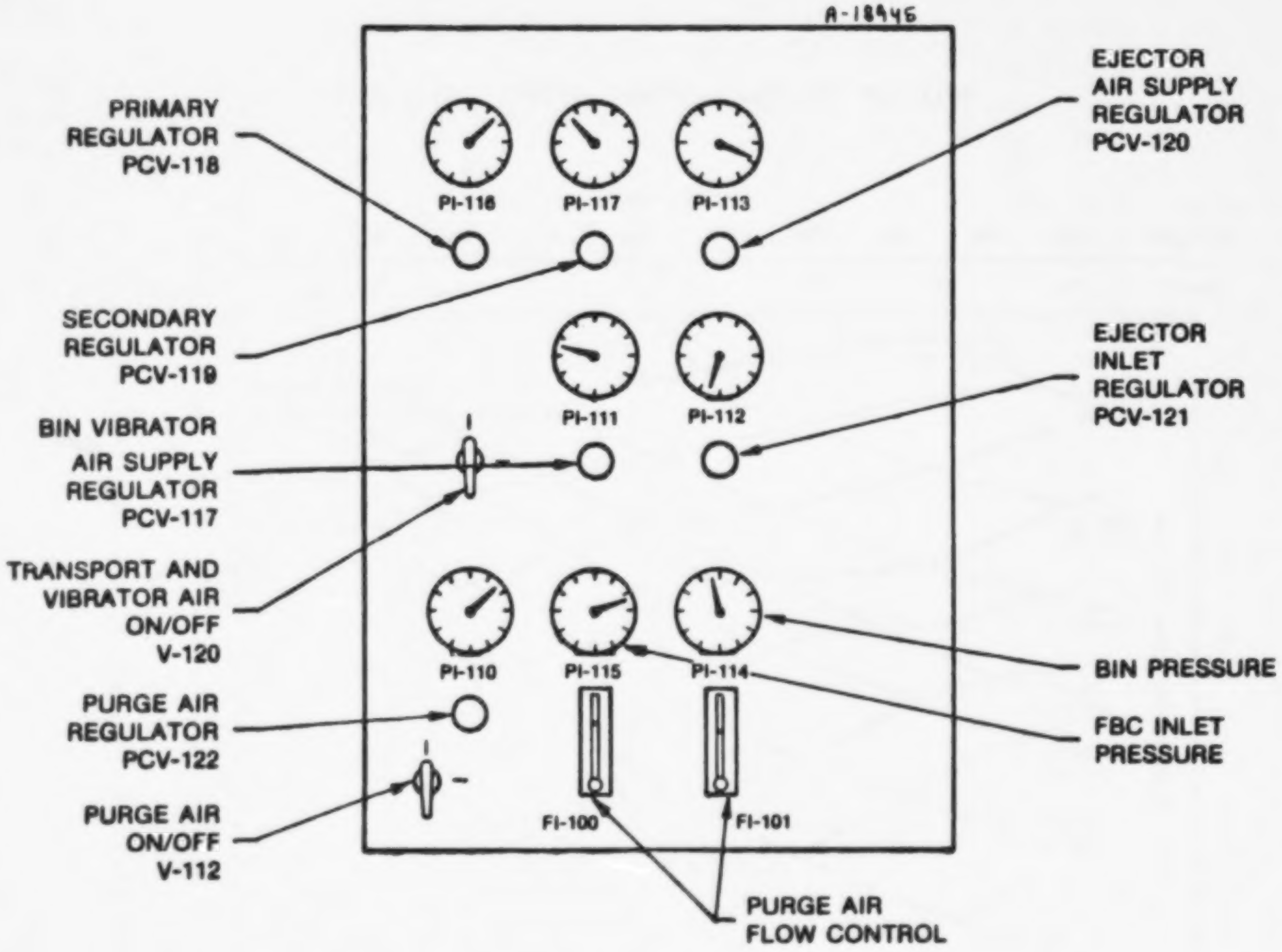

A-18946
PRIMARY REGULATOR PCV-118
SECONDARY REGULATOR PCV-119
BIN VIBRATOR AIR SUPPLY REGULATOR PCV-117
TRANSPORT AND VIBRATOR AIR ON/OFF V-120
PURGE AIR REGULATOR PCV-122
PURGE AIR ON/OFF V-112
PI-116
PI-117
PI-113
PI-111
PI-112
PI-110
PI-115
PI-114
FI-100
FI-101
EJECTOR AIR SUPPLY REGULATOR PCV-120
EJECTOR INLET REGULATOR PCV-121
BIN PRESSURE
FBC INLET PRESSURE
PURGE AIR FLOW CONTROL

Figure 2-17. Pneumatic control console.

TABLE 2-2. SOLIDS FEED SYSTEM INSTRUMENTATION

Measurement	Range	P&ID Identification 7255-101D	P&ID Loc. 7255-101D
Coal feedrate	0-50 kg/hr 22-110 lbs/hr	HRC-100	C-7
Sorbent feedrate	0-22 kg/hr 0-50 lbs/hr	HRC-101	C-7
Ash feedrate	0-8 kg/hr 0-20 lbs/hr	HRC-102	B-7
Bin coal weight	0-906 kg/hr 0-2000 lbs	WE-100/WI-100-1	C-8
Bin sorbent weight	0-453 kg/hr 0-1000 lbs	WE-101-WI-100-2	C-8
Bin ash weight	0-226 kg/hr 0-500 lbs	WE-102/WI-100-3	B-8
Coal bin vibrator timer	3-120 sec	HS-113/LV-113	C-8
Sorbent bin vibrator timer	3-120 sec	HS-114/LV-114	C-8
Ash bin vibrator timer	3-120 sec	HS-115/LV-115	B-8
Vibrator supply air pr.	0-1102 kPa 0-160 psi	PI-111/PEV-117	A-8
Primary air supply reg.	0-1102 kPa 0-160 psi	PI-116/PEV-117	A-8
Secondary air sply. reg. flow element inlet pr.	0-1102 kPa 0-160 psi	PI-117/PEV-119	A-8
Flow element air temp.	0-93°C 32-200°F	FE-118/TI-100-3	A-7/3-7
Flow element diff. pr.	0-7.5 kPa 0-15" H_2O	DPI-113	A-7
Ejector supply pressure	0-1102 kPa 0-160 psi	PEV-120/PI-113	B-6
Mixer supply pressure	0-34.5 kPa 0-5 psi	PCV-121/PI-112	B-7
Pneumatic inlet FBC pr.	0-34.5 kPa 0-5 psi	PI-115	B-5
Purge air	0-1102 kPa 0-160 psi	FI-100/FI-101	B-6

TABLE 2-3. FLUIDIZED BED COMBUSTION UNIT INSTRUMENTATION

Measurement	Range	P&ID Identification 7255-101D	P&ID Location 7255-101D
Air plenum box pressure	0-37 kPa 0-150" H_2O	PI-103	B-5
Air plenum box temp.	0-538°C 32-1000°F	TE-300/TI-300-1	B-4
ΔP distributor	0-5 kPa 0-20" H_2O	DPI-107	B-5
ΔP bed density	0-7.5 kPa 0-30" H_2O	DPI-107	C-5
ΔP bed height	0-7.5 kPa 0-30" H_2O	DPI-106	C-5
Freeboard pressure	0-25 kPa 0-100" H_2O	PI-104	D-5
Bed temperature probes	0-1204°C 32-2200°F	TE-301/TI-300-2 TE-305/TI-300-3 TE-302/TAH-302	B-4 C-4 C-4
Freeboard temp. probes	0-1204°C 32-2200°F	TE-303/TI-300-3 TE-304/TI-300-4	D-4 D-4
Heat exchanger bulk water inlet temperature	16-38°C 60-100°F	TE-200/TI-200-1	D-6
Heat exchanger water inlet pressure	0-689 kPa 0-100 psi	PI-200	D-5
Differential Orifice I pressure	0-7.5 kPa 0-30" H_2O	DPI-200	D-5
Differential Orifice II pressure	0-7.5 kPa 0-30" H_2O	DPI-201	C-5
Heat exchanger bulk outlet temperature	16-100°C 60-212°F	TE-202/TI-200-2	C-4
	Adjust to 60°C 140°F		
Heat exchanger -1 outlet temperature	16-100°C 60-212°F	TE-201-A/TI-200-3	D-4
" " -2 "	↓	-B -4	D-4
" " -3 "		-C -5	↓
" " -4 "		-D -6	
" " ↓ "		↓ ↓	
" " "			
" " -10 "		-J -12	

The heat exchanger water supply system has been provided with a high and low water flowrate orifice. This configuration allows for accurate measurements and a minimum changeover service requirement. The two branches of the water supply system can be installed and used in separate cooling circuits such as a freeboard heat exchanger circuit and the bed heat exchanger circuit. Each branch flow can be monitored independently.

2.7.2.4 Flue Gas Cleanup System Instrumentation

The flue gas cleanup system instrumentation consists principally of temperature and pressure sensors and indicating devices located on the flue gas ducting and control console respectively. The only controls are valves controlling the flowrate through the secondary cyclone and thereby setting the pressure drops and the coolant control valves for the flue gas cooler. Like the heat exchanger coolant manifold for the combustor, the coolant manifold for the flue gas cooler has a high and low flow orifice branch to permit accurate flow measurements to be made while accommodating a high turndown capability. The flue gas exhaust temperature is principally controlled by adding and subtracting heat exchanger surface. The temperature and pressure measurement capabilities of the provided flue gas cleanup system are listed in Table 2-4.

Certain operating modes are undesirable because they may result in equipment damage. These modes of operation are indicated to the operator by warning lights on the control console. Undesirable operating conditions are excess coolant water temperatures, high baghouse inlet temperatures and high differential pressures across the baghouse.

2.7.3 Process Variables – Oxygen and Combustibles Analyzer

To gain close control over the combustion process, the oxygen concentration (excess air) must be monitored. A Teledyne combustion process analyzer Moder 9700 has been provided for this purpose. The analyzer can be divided into the oxygen and combustibles monitoring sections.

The oxygen analyzer employs an electrochemical transducer to provide an electrical signal that is directly proportional to the oxygen concentration in the gas phase immediately adjacent to its sensing surface.

TABLE 2-4. FLUE GAS CLEANUP SYSTEM INSTRUMENTATION

Measurement	Range	P&ID Identification 7255-101D	P&ID Location 7255-101D
Primary Cyclone			
Inlet temperature	0-1094°C (32-2000°F)	TE0304/TI-300-3	D-4
ΔP primary cyclone	0-3.8 kPa (0-15" H_2O)	DPI-109	D-3
Downspout temperature	0-816°C (32-1500°F)	TE-109/TI-102-6	D-3
Secondary Cyclone			
Inlet temperature	0-927°C (32-1700°F)	TE-107/TI-102-5	D-3
Inlet static pressure	0-7.5 kPa (0-30" H_2O)	PI-106	D-3
ΔP primary to secondary inlet	0.75 kPa (0-30" H_2O)	DPI-111	D-3
ΔP secondary inlet to outlet	0-3.8 kPa (0-15" H_2O)	DPI-110	D-3
Downspout temperature	0-816°C (32-1500°F)	TE-110/TI-102-8	D-3
Outlet temperature	0-3.8 kPa (32-2000°F)	TE-108/TI-102-7	D-2
Flue Gas Heat Exchanger			
Gas inlet temperature	0-3.8 kPa (32-2000°F)	TE-116/TI-102-9	C-1
Flue gas cooler outlet 1	0-288°C (32-550°F)	TE-117/TI-100-4	B-2
Flue gas cooler outlet 2	0-288°C (32-550°F)	TE-111/TI-100-5	B-2
Heat exchanger bulk water inlet temp.	16-38°C (60-100°F)	TE-203/TI-201-1	C-3
Differential Orifice I pressure	0-7.5 kPa (0-30" H_2O)	DPI-202	C-3
Differential Orifice II pressure	0.7.5 kPa (0-30" H_2O)	DPI-203	C-3
Heat exchanger bulk outlet temperature	16-38°C (60-212°F)	TE-205/TI-201-2	B-2
Heat exchanger -1 outlet temperature	16-38°C (60-212°F)	TE-201-A/TI-201-3	C-1
" " -2 " "	↓	-B/TI-201-3	↓
" " ↓ " "		↓	
" " -10 " "		-J/TI-201-12	
Electrostatic Precipitator			
Inlet gas temperature	0-288°C (32-550°F)	TE-113/TI-102-10	B-3
Baghouse			
ΔP inlet-outlet	0-2.5 kPa (0-10" H_2O)	DPI-112	B-2
Inlet gas temperature	0-260°C (32-500°F)	TE-112/TI-100-6	B-2
Pulse plenum pressure	0-110^2 (0-160 psi)	PI-108	B-2

T-808

One of the three available ranges of analysis is 0 to 25 percent so that air (2.9 percent oxygen) may be used to calibrate the sensitivity of the analyzer. It is equipped with an exceptionally accurate 12.7 cm (5 inch) panel meter for direct readout of the analysis. An output signal of 0 to 1 V D.C. is also available.

The combustibles monitor consists of controls, readout meters, alarm relays, sensors, flowmeters, valves and heaters. A prominent meter displays the gas concentration at the detection point as a percentage of the combustible gases and is graduated from 0 to 5 percent combustibles. An alarm bell will sound off should the concentration exceed a predetermined value.

The complete description of the equipment, operation and service requirements is given in the instruction manual for the oxygen and combustibles system Model 9700.

2.7.4 Safety Interlocks

The following system safety interlocks are provided to reduce the danger of failure. Attended operation, however, is required to monitor the operation of the facility. All circuits are protected by circuit breakers for overload conditions. The devices are listed in Table 2-5.

2.7.5 Instrument Listings

The FBC Test Rig has been instrumented with temperature, pressure and other sensors to allow measurements to be made for purposes of safety, energy and mass balance's trend analysis and to generate those conditions of interest for pollution control tests. The following Tables 2-6 and 2-7 list the instruments, their function and the location on the system P&ID. The tables, together with the P&ID, allow for quick identification during tests.

TABLE 2-5. SAFETY INTERLOCKS

Condition	Device	Response
High blower inlet temperature	Temp. switch	Power off/heater off/ solids off
Low air velocity	ΔP switch	Solids off/heater off
Bed overtemperature	Temp. switch	Solids off
Coolant overtemperature	Temp. switch	Solids off
High baghouse ΔP	ΔP switch	Red light
High cleanup device temperature	Temp. switch	Red light
Low water pressure-bed	ΔP switch	Red light
Low water pressure cooler	ΔP switch	Red light
Solids level indicator - low -	Transducers	Red light
High combustibles	Analyzer	Bell

TABLE 2-6. INSTRUMENT NOMENCLATURES

Identification	Location	Indication	Function
Temp. Element			
TE-100	D-7	TI-100-1	Main orifice inlet
TE-101	D-6	TI-101	Heated sheath T. contr.
TE-102	D-6	TIC-102	Heater air temp. contr.
TE-103	C-6	TI-102-2	Sec. air temp. leg 1
TE-104	C-6	TI-102-3	" " " " 2
TE-105	C-6	TI-102-4	" " " " 3
TE-106	D-6	TI-102-1	Main air temperature
TE-107	D-3	TI-102-5	Pr. cyclone outlet gas temp.
TE-108	D-2	TI-102-7	Sec. " " " "
TE-109	D-3	TI-102-6	Primary cyclone dipleg
TE-110	D-2	TI-102-8	Sec. cyclone dipleg
TE-111	B-2	TI-100-5	Flue gas cooler outlet 1
TE-112	B-2	TI-100-6	Baghouse inlet
TE-113	B-2	TI-102-10	ESP inlet
TE-114	B-3	TI-102-11	Stack temp.
TE-115	A-3	TI-100-2	FGR orifice inlet
TE-116	C-2	TI-102-9	Flue gas cooler inlet
TE-117	B-2	TI-100-4	Flue gas cooler outlet 2
TE-118	B-7	TI-100-3	Flow element inlet air temp. solid feed system
TE-200	D-6	TI-200-1	Fluid. bed exchanger water in
TE-201A	D-4	TI-200-3	Fluid. bed exchanger 1 " out
" B	"	" 4	" " " 2 " "
" C	"	" 5	" " " 3 " "
" D	"	" 6	" " " 4 " "
" E	"	" 7	" " " 5 " "
" F	"	" 8	" " " 6 " "
" G	"	" 9	" " " 7 " "
" H	"	" 10	" " " 8 " "
" I	"	" 11	" " " 9 " "
" J	"	" 12	" " " 10 " "
TE-202	C-4	TI-200-2	" " " bulk out
TE-203	C-3	TI-201-1	Water inlet FG cooler
TE-204A	C-2	TI-201-3	Water outlet exchanger 1
" B	"	" 4	" " " 2
" C	"	" 5	" " " 3
" D	"	" 6	" " " 4
" E	"	" 7	" " " 5
" F	"	" 8	" " " 6
" G	"	" 9	" " " 7
" H	"	" 10	" " " 8
" I	"	" 11	" " " 9
" J	"	" 12	" " " 10
TE-205	B-1	TI-201-2	Water bulk out FG cooler

TABLE 2-6. Continued

Identification	Location	Indication	Function
TE-300	B-4	TI-300-1	Air plenum temperature
TE-301	B-4	TI-300-2	Fl. bed temperature I
TE-302	C-4	TAH-302	Fl. bed overtemperature alarm
TE-303	D-4	TI-300-4	Lower freeboard temperature
TE-304	D-4	TI-300-5	Upper freeboard temperature
TE-305	C-4	TI-300-3	Fl. bed temperature II
Temp. Switch			
TS-100	D-7		Blower overtemperature
TS-200	C-3	TAH-200	Water out overtemp./light
TS-201	B-1	TAH-201	Water out overtemp. cooler
TS-102	B-2	TAH-102	Baghouse overtemp. alarm light
Flow Orifice			
FO-200	C-3		Water restr. dipleg primary
FO-201	C-3		" " " secondary
Hand Rheostat Contr			
HRC-100	C-7		Auto-transf. vibrators coal
HRC-101	C-7		" " " sorbent
HRC-102	B-7		" " " flyash
HS-113	C-8		Timer-coal bin vibrator
HS-114	C-8		Timer-sorbent bin vibrator
HS-115	B-8		" ash " "
HS-116	B-8		" ash " "
Pressure Indicator			
PI-100	D-7		Main orifice inlet pressure
PI-102	C-6		Sec. air plenum pressure
PI-103	B-5		Plenum box pressure
PI-104	D-5		Freeboard pressure
PI-105	A-4		FGR-orifice inlet pressure
PI-106	D-3		Sec. cyclone inlet pressure
PI-107	B-3		Stack pressure
PI-108	B-2		Baghouse air plenum pressure
PI-109	A-8		Compressor supply pressure
PI-110	A-7		Purge air pressure
PI-111	A-8		Vibrator line pressure
PI-112	B-7		Reg. mixing chamber pressure
PI-113	B-6		Ejector pressure
PI-114	B-7		Mixing chamber pressure
PI-115	B-5		Injection outlet pressure
PI-116	B-7		Regulator pressure
PI-117	B-7		Flow element inlet pressure

TABLE 2-6. Continued

Identification	Location	Indication	Function
PI-200	D-5		Water inlet pressure
PS-200	C-3	PAL-200	Low-pr. alarm light dipleg 1
PS-201	C-3	PAL-201	Low pr. alarm light dipleg 2
Diff. Pressure			
DPI-100	D-7		Mixing ch. ΔP
DPI-101	D-7		Main orifice indicator
DPI-102	C-6		Secondary air leg 1
DPI-103	C-6		" " " 2
DPI-104	C-6		" " " 3
DPI-105	B-5		Distributor plate
DPI-106	C-5		Bed height pressure
DPI-107	C-5		Bed density
DPI-108	A-4		FGR orifice
DPI-109	D-3		Primary cyclone
DPI-110	D-3		Sec-outlet-sec. cyclone
DPI-111	D-3		Prim-secondary-sec. cyclone
DPI-112	B-2		Baghouse diff.
DPI-113	A-7		Flow element diff. pr.
DPI-200	D-5		Bed exchanger main water
DPI-201	C-5		" " sec.. "
DPI-202	C-2		Cooler-exchanger main water
DPI-203	C-2		Cooler-exchanger sec. water
Diff. Pres. Sys.			
DPS-100	D-6		Low air flow sensor
DPSH-106	C-6		Bed height control
DPSL-106	C-6		Bed height control
DPS-107	B-2		Baghouse high ΔP height
Flow Alarm			
FAL-100	D-6		Low air flow light
Pres. Contr. Valve			
PCV-117	A-8		Vibrator pressure regulator
PCV-118	A-7		Transport air line pr. reg.
PCV-119	A-7		" " " " "
PCV-120	B-7		Ejector pressure regulator
PCV-121	B-7		Mixing chamber pr. regulator
PCV-122	A-7		Purge air pressure regulator
PCV-123	A-7		Baghouse pulse pressure

TABLE 2-6. Continued

Identification	Location	Indication	Function
Pr. Safety Valve			
PSV-100	C-7		Bin pr. relief valve
PSV-101	B-7		Mixing chamber pr. rel valve
Valve			
V-111	D-8		Mixing chamber inlet
V-112	A-7		Air supply shutoff
V-113	A-7		Air supply shutoff
V-114	B-5		Air shutoff ash valve
V-115	B-4		Ash valve
V-120	A-7		Air supply shutoff
V-121	B-5		Solids transport shutoff
V-204	C-3		Pr. dipleg water
V-205	C-3		Sec. dipleg water
Flow Contr. Valves			
FCV-100	D-7		Main air flow
FCV-101	D-6		Secondary air
FCV-102	C-6		Secondary air heater bypass
FCV-103	C-5		Secondary air leg 1
FCV-104	C-5		" " " 2
FCV-105	C-5		" " " 3
FCV-106	D-3		Secondary cyclone bypass dampr
FCV-107	D-3		" " sec. inlet
FCV-108	D-3		Secondary cyclone prim. inlet
FCV-109	B-5		
FCV-110	D-8		Flue gas recirculation contr.
FCV-200	D-5		Bed exch. prim. wtr. control
FCV-201	C-5		" " sec. " "
FCV-206	C-2		Cooler exchr. prim. wtr. contr
FCV-207	C-2		Cooler exchr. sec. wtr. contr.
Selector Valve			
SV-202A	D-5		Bed exchanger selector valve
" B	"		" " " "
" C	"		" " " "
" D	"		" " " "
" E	"		" " " "
" F	"		" " " "
" G	"		" " " "
" H	"		" " " "
" I	"		" " " "
" J	"		" " " "

TABLE 2-6. Continued

Identification	Location	Indication	Function
SV-208A	C-2		Bed exchanger selector valve
" B	"		" " " "
" C	"		" " " "
" D	"		" " " "
" E	"		" " " "
" F	"		" " " "
" G	"		" " " "
" H	"		" " " "
" I	"		" " " "
" J	"		" " " "
NV-203A	D-4		Bed check valves exchanger
" B	"		" " " "
" C	"		" " " "
" D	"		" " " "
" E	"		" " " "
" F	"		" " " "
" G	"		" " " "
" H	"		" " " "
" I	"		" " " "
" J	"		" " " "
NV-209A	C-1		Cooler check valves exchanger
" B	"		" " " "
" C	"		" " " "
" D	"		" " " "
" E	"		" " " "
" F	"		" " " "
" G	"		" " " "
" H	"		" " " "
" I	"		" " " "
" J	"		" " " "
Solenoid Valve			
SOV-113	C-8		Vibrator contr. solenoid valve
SOV-114	B-8		" " " "
SOV-115	B-8		" " " "
SOV-116	A-5	ES-116	Bed height sol. contr. valve
SOV-117	B-8		Vibrator contr. sol. valve
EC-100	D-7		Blower contactor
WE-100	C-8	WI-100-1	WAL 100 coal wt. ind/alarm log
WE-101	C-8	WI-100-2	WAL 101 sorbent " " " "
WE-102	B-8	WI-100-3	WAL 102 ash " " " "
FI-100	B-6		Purge flow meter
FI-101	B-6		" " "

TABLE 2-7. TEMPERATURE SELECTOR SWITCH INDICATION

Temperature Indicator	Temperature Element	Description
TI-100-1	TE-100	Main orifice inlet
TI-100-2	TE-115	FGR orifice inlet
TI-100-3	TE-118	Flow element inlet-solids feed
FI-100-4	TE-117	Flue gas cooler outlet
TI-100-5	TE-111	" " " "
TI-100-6	TE-112	Baghouse inlet
TI-102-1	TE-106	Heater air temperature
" 2	TE-103	Secondary air inlet I
" 3	TE-104	Secondary air inlet II
" 4	TE-105	Secondary air inlet III
" 5	TE-107	Primary cyclone outlet
" 6	TE-109	Primary cyclone dipleg
" 7	TE-108	Secondary cyclone outlet
" 8	TE-110	Secondary cyclone diplet
" 9	TE-116	Flue gas cooler inlet temperature
" 10	TE-113	ESP inlet temperature
" 11	TE-114	Stack temperature
TI-200-1	TE-200	Fluidized bed heat exchanger water in
" 2	TE-202	Fluidized bed heat exchanger water out
" 3	TE-201A	Heat exchanger 1 out
" 4	" B	" " 2 "
" 5	" C	" " 3 "
" 6	" D	" " 4 "
" 7	" E	" " 5 "
" 8	" F	" " 6 "
" 9	" G	" " 7 "
" 10	" H	" " 8 "
" 11	" I	" " 9 "
" 12	" J	" " 10 "
TI-201-1	TE-203	Flue gas cooler water inlet
" 2	TE-205	Flue gas cooler water outlet
" 3	TE-204A	Heat exchanger 1 out
" 4	" B	" " 2 "
" 5	" C	" " 3 "
" 6	" D	" " 4 "
" 7	" E	" " 5 "
" 8	" F	" " 6 "
" 9	" G	" " 7 "
" 10	" H	" " 8 "
" 11	" I	" " 9 "
" 12	" J	" " 10 "

SECTION 3

FACILITY OPERATION

This section describes the operation and operating characteristics of the system and subsystems. The operation of the overall system depends on many variables and conditions. Not all variables are independent, and a judicious choice of the principal variables must be made to obtain the desired test operation. System characteristics are described in Section 3.1, whereas subsystems are described in the various following sections.

3.1 SYSTEM CHARACTERISTICS

The FBC test rig has been designed and constructed to operate in the following basic ranges:

• Coal feedrate	— 10 to 50 kg/hr (22 to 110 lbm/hr)
• Sorbent feedrate	— 0 to 25 kg/hr (0 to 50 lbm/hr)
• Excess air	— 10 to 300 percent
• Bed temperature	— 750°C to 1110°C (1380°F to 2010°F)
• Fluidizing velocity	— 1 to 5 mps (3 to 16 fps)

The facility is capable of attaining these ranges, but since the variables listed above are not independent of each other, the ranges may not all be attainable at the same time.

The facility has been sized for an optimum operating condition. This condition was selected near the upper limits of the given ranges to give the test rig the greatest possible accuracy. The design point conditions are shown in Table 3-1. The resulting energy balance in the combustor is shown in Table 3-2. The basic operating ranges define the operating envelope to the degree that a bed cross-sectional area can be selected. For this

TABLE 3-1. DESIGN POINT CONDITIONS

Coal feed rate ($\dot{m}_c$)	31.7 kg/hr (70 lbm/hr)
Heating value (h_v)	23,400 kJ/kg (10,000 Btu/lbm)
Air rate ($\dot{m}_a$) (20% excess air)	289 kg/hr (3990 sdm^3) 638 lbm/hr (141 scfm)
Sorbent feed rate (m_{sorb})	9.98 kg/hr (22 lbm/hr)
(limestone = 50% CaO by wt Cals = 3 3% sulfur coal)	
Bed temperature (T)	843°C (1,550°F)
Fluidizing velocity (U_o)	1.83 m/sec (6 ft/sec)
Heat removal by cooling (Q_{tubes})	455,800 kJ (430,000 Btu/hr)
Top particle size	0.159 cm (1/16 inch)

TABLE 3-2. COMBUSTOR DESIGN POINT ENERGY BALANCE kJ/hr (Btu/hr)

Energy content of coal		742,000		(700,000)
Energy added to fluidizing air	241,680		(228,000)	
Energy removed by cooling tubes	455,800		(430,000)	
Energy lost through insulated walls	31,800		(30,000)	
Energy lost to offtake ash	4,240		(4,000)	
Energy lost to elutriated solids	8,480		(8,000)	
	742,000	742,000	(700,000)	(700,000)

facility, the area has been sized as 968 to 1935 cm^2 (150 to 300 in^2) in order to meet all specified conditions for fluidizing velocity and excess air. Figure 3-1, (Air flowrate versus coal flowrate) and Figure 3-2 (Fluidizing velocity versus total gas flowrate) show the effects of changing a particular variable. Figure 3-2 also shows that at least two combustor cross-sectional areas are required to accommodate the entire range of superficial velocities specified. This was a necessary compromise, since not all components can tolerate the high turndown specified and still perform their function. Sizing of the test rig and its components was based on the design point conditions and the effects of varying the operating parameters. The values shown in Table 3-3 reflect the maximum and minimum conditions. Table 3-4 shows the pressure distribution at the design point; Figure 3-3 shows the locations where temperature, pressure, and flow are measured in the system.

Since the flow and temperature ranges are not independent of each other, setting the flow or temperature at any one location will preclude the attaining of the entire listed range at other locations. It is noted also that the total mass air flowrate is composed of two components. They are the main air flow and the solids transport air. To achieve a desired air preheat rate the composite temperature must be calculated to arrive at an accurate value.

Initial tests have indicated that all variables specified as basic operating ranges can be obtained. The ranges specified, however, were such that they cannot be obtained without requiring the reconfiguration of at least the combustor section and the exchange of the distributor plate. The fluidizing velocity is perhaps the variable causing the greatest inconvenience, particularly during startup, if low velocities are desired. The attainable fluidizing velocity is dependent on the bed material density and size, the distributor pressure drop, the combustor size and the desired operating temperature. Low initial actual gas volume flowrates due to low temperature cause the bed not to fluidize. Increasing the flowrates with high preheat temperatures results in high pressure drops across the distributor which may limit the maximum attainable flow. Should it not be possible to inject sufficient air through the distributor, a secondary air port may be utilized for this purpose during startup.

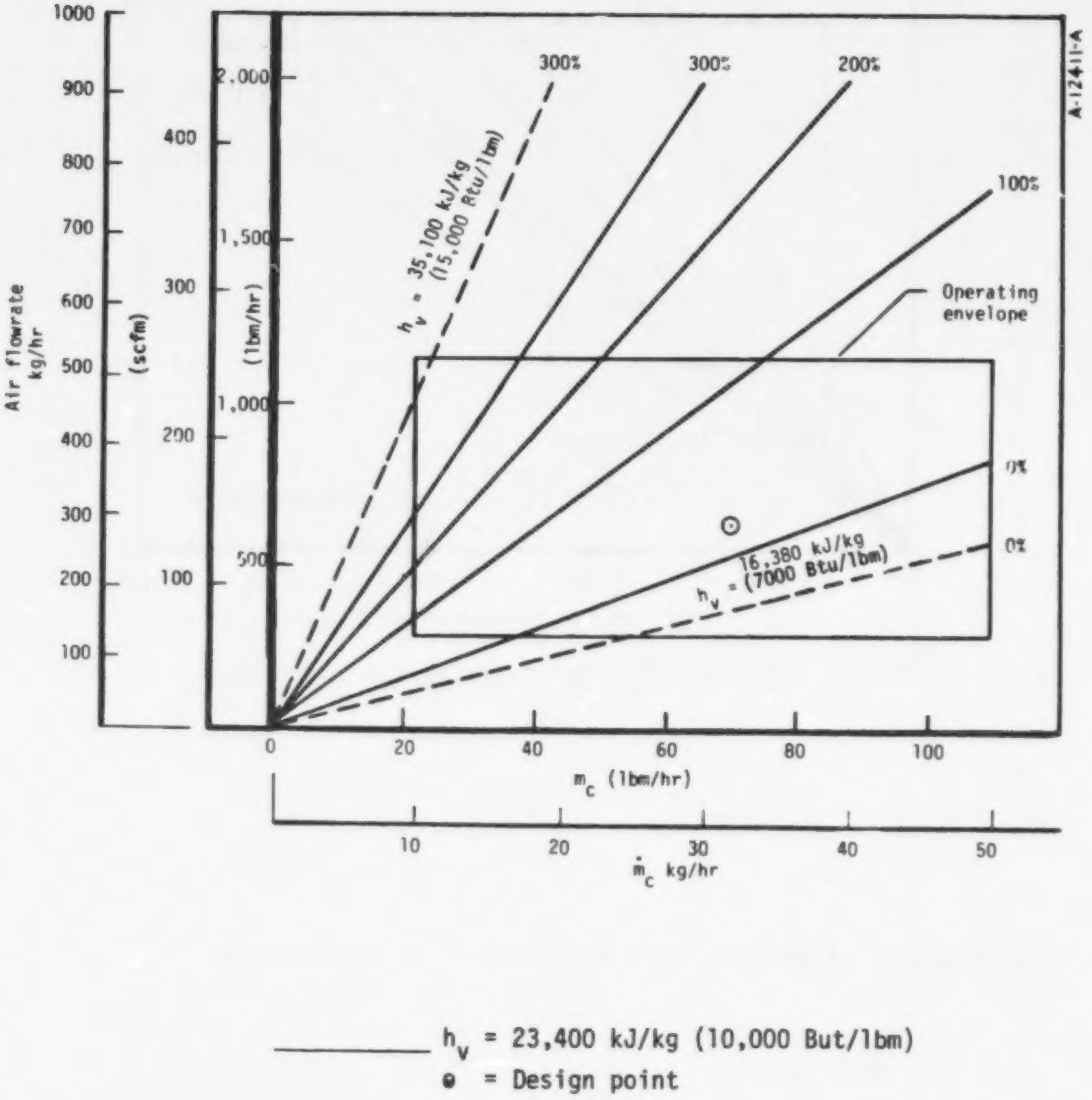


Figure 3-1. Air flowrate versus coal flowrate.

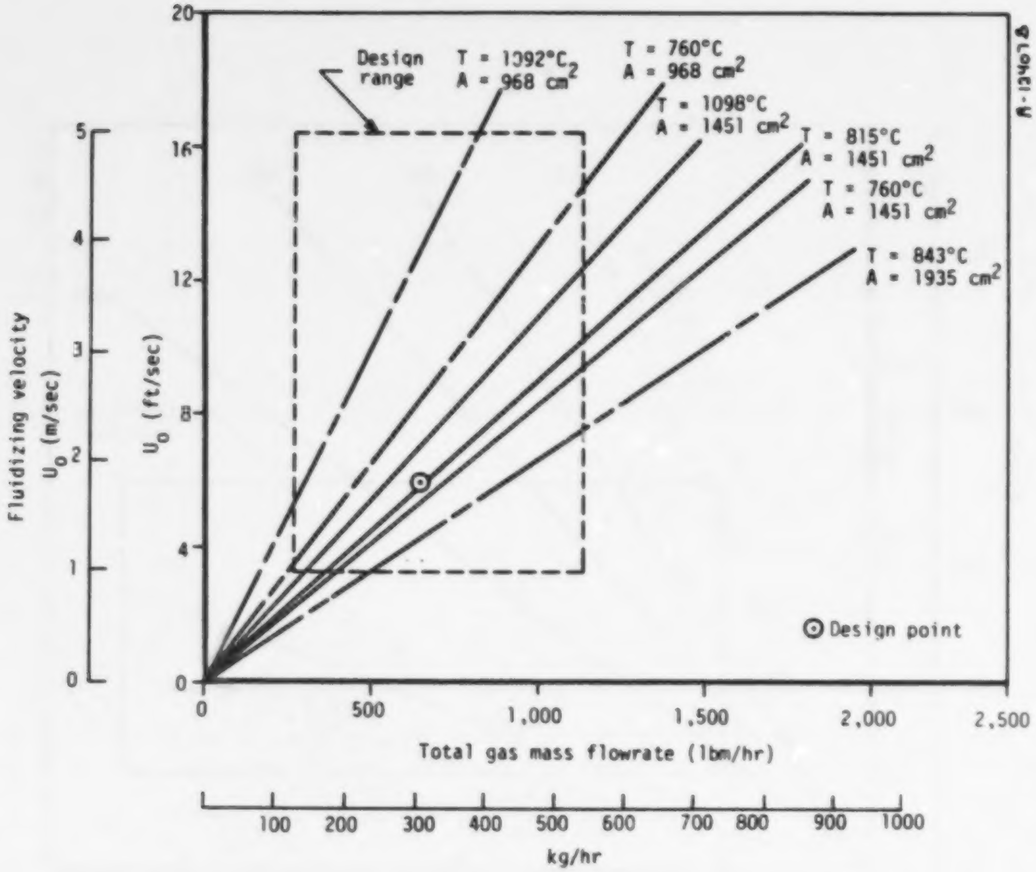


Figure 3-2. Fluidizing velocity versus total gas flowrate.

TABLE 3-3. FLOW AND TEMPERATURE DESIGN RANGES

Location[a]	Flow		Temperature	
1	1133 - 7080 sdm^3/min	(40 - 250 scfm)	0°C - 50	(30°F - 120°F)
2	1133 - 7080 sdm^3/min	(40 - 250 scfm)	0°C - 170°C	(30°F - 340°F)
3	1133 - 7080 sdm^3/min	(40 - 250 scfm)	15°C - 454°C	(60°F - 850°F)
4	569 - 3414 sdm^3/min	(20 - 120 scfm)	15°C - 454°C	(60°F - 850°F)
5	0 - 853 sdm^3/min	(0 - 30 scfm)	15°C - 65°C	(60°F - 150°F)
6	0 - 1133 sdm^3/hr	(0 - 40 lbm/hr)	15°C - 50°C	(60°F - 120°F)
7	0 - 1416 sdm^3/hr	(0 - 50 lbm/hr)	15°C - 50°C	(60°F - 120°F)
8	10 - 50 kg/hr	(22 - 110 lbm/hr)	15°C - 50°C	(60°F - 120°F)
9	0 - 148 kg/hr	(0 - 326 lbm/hr)	15°C - 50°C	(60°F - 150°F)
10	0 - 378 dm^3/min	(0 - 100 gpm)	15°C - 60°C	(60°F - 140°F)
11	97.5 - 654 kg/hr	(215 - 1442 lbm/hr)	15°C - 1204°C	(60°F - 2200°F)
12	3.6 - 18 kg/hr	(8 - 40 lbm/hr)	15°C - 1093°C	(60°F - 2000°F)
13	79 - 650 kg/hr	(175 - 1434 lbm/hr)	15°C - 1204°C	(60°F - 2200°F)
14	0 - 1.4 kg/hr	(0 - 3 lbm/hr)	15°C - 1093°C	(60°F - 2000°F)
15	78 - 650 kg/hr	(172 - 1434 lbm/hr)	15°C - 1149°C	(60°F - 2100°F)
16	0 - 114 dm^3/min	(0 - 30 gpm)	15°C - 60°C	(60°F - 140°F)
17	78 - 650 kg/hr	(172 - 1434 lbm/hr)	15°C - 260°C	(60°F - 500°F)
18	78 - 650 kg/hr	(172 - 1434 lbm/hr)	15°C - 260°C	(60°F - 500°F)
19	78 - 650 kg/hr	(172 - 1434 lbm/hr)	15°C - 260°C	(60°F - 500°F)
20	0 - 1700 sdm^3/min	(0 - 60 scfm)	150°C - 260°C	(300°F - 500°F)
21	78 - 650 kg/hr	(172 - 1434 lbm/hr)	15°C - 260°C	(60°F - 500°F)

[a] See Figure 3-3

TABLE 3-4. DESIGN POINT PRESSURE DISTRIBUTION

Location[a]	kPa	Pressure (psia)
1	99.90	(14.5)
2	121.95	(17.7)
3	121.95	(17.7)
4	121.95	(17.5)
5	118.51	(17.2)
6	101.28	(14.7)
7	101.28	(14.7)
8	101.28	(14.7)
9	118.51	(17.2)
10	406.51	(59)
11	113.00	(16.4)
12	111.62	(16.2)
13	110.24	(16.0)
14	108.86	(15.8)
15	107.48	(15.6)
16	413.4	(60)
17	106.80	(15.5)
18	105.42	(15.3)
19	104.04	(15.1)
20	103.35	(15.0)
21	103.35	(15.0)

[a] See Figure 3-3

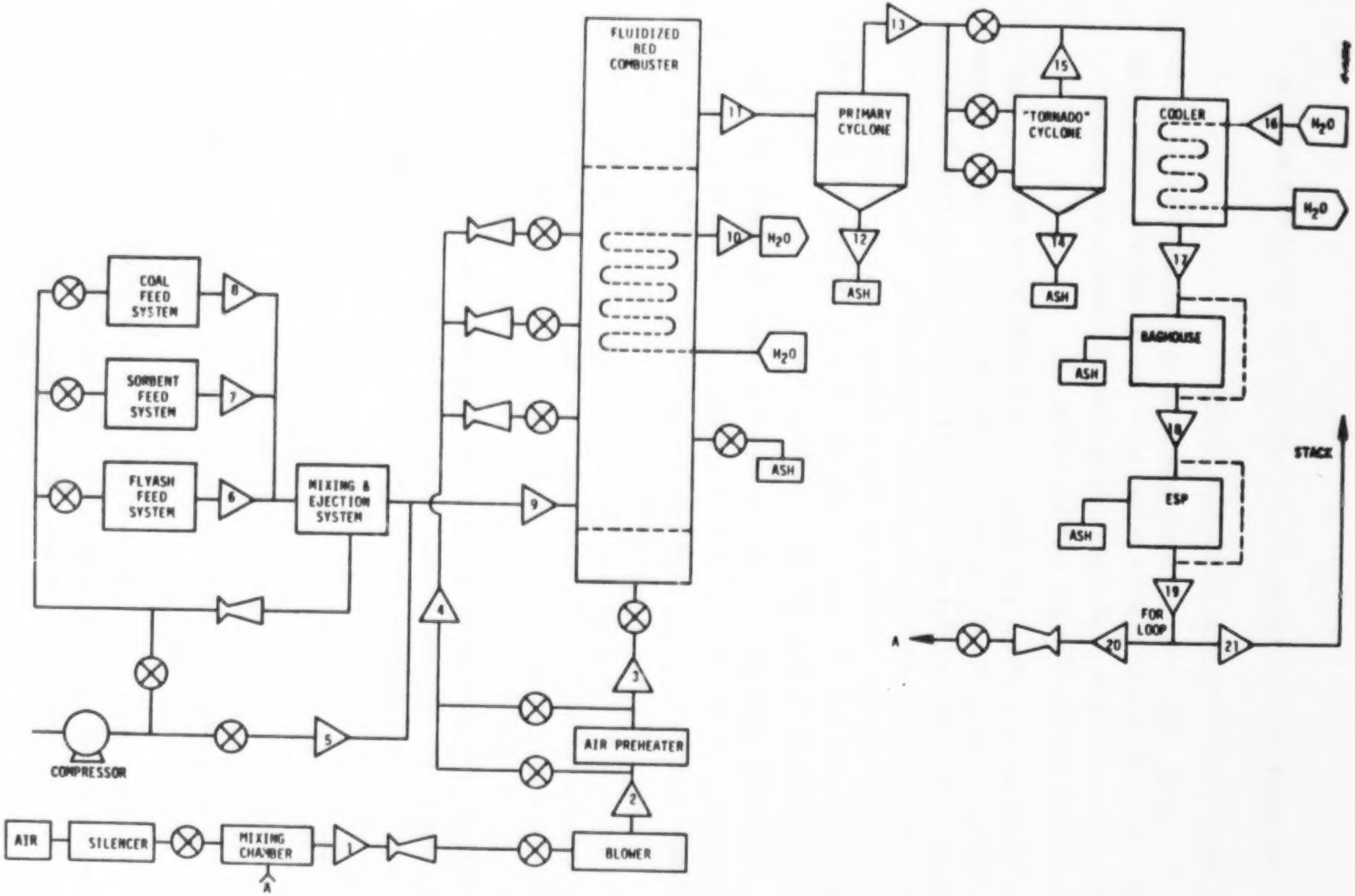

FLUIDIZED BED COMBUSTER
PRIMARY CYCLONE
"TORNADO" CYCLONE
COOLER
H_2O
H_2O
16
13
15
11
12
14
17
ASH
ASH
ASH
10
H_2O
H_2O
BAGHOUSE
ASH
18
STACK
ESP
ASH
ASH
19
FOR LOOP
A
20
21
COAL FEED SYSTEM
SORBENT FEED SYSTEM
FLYASH FEED SYSTEM
8
7
6
MIXING & EJECTION SYSTEM
9
4
3
5
AIR PREHEATER
2
COMPRESSOR
AIR
SILENCER
MIXING CHAMBER
A
1
BLOWER

Figure 3-3. FBC test rig system schematic.

The operating limitations are indicated in the following subsections.

3.1.1 Operating Preparations and Configurations

To accommodate a test plan and obtain the desired operating parameters, the facility will have to be set up in the appropriate configuration. The principal subsystems requiring configuration adjustments are the combustor section and the flue gas cleanup system.

Variables that affect the combustor configuration are the coal feedrate, bed temperature, fluidizing velocity and bed height. Figure 3-2 shows the gas mass flowrate restrictions for a particular combustor size for the range of fluidizing velocities or operating temperatures. The total gas mass flowrate will dictate a coal flowrate for a certain excess air condition (Figure 3-1). The coal flowrate in turn will dictate the bed energy removal rate and the amount of heat exchanger surface area.

The first component that must be selected after the combustor cross-sectional area has been determined is the distributor plate. The guideline to be followed here is to have a pressure drop across the plate of 0.996 to 3.98 kPa (4 to 16 inches) of H_2O or 30 percent of the bed pressure drop. The pressure drop is influenced by the gas mass flowrate, the gas temperature and slightly by absolute pressure. The distributor plates provided are perforated plates with varying numbers of holes per area. Four plates are provided with the following number of holes for the 1451 cm^2 (225 in^2) combustor area covering the indicated flow ranges. The flow capability is obviously proportional with the number of holes. The effect of preheat temperatures can be approximated by treating the holes as orifices. The flow through one 0.254 cm (0.100 inch) diameter hole at 21°C (70°F) and 101.3 kPa (14.7 psia) has been measured to correspond to 10.8 to 21.54 dm^3/min (0.38 to 0.75 cfm) for the 0.996 to 3.98 kPa (4 to 16 inch) H_2O pressure drop. (See Table 3-5.)

Select the appropriate plate and install it into the air plenum chamber. Be sure to use a Fiberfrax or similar gasket at the interface as shown in the drawing to minimize side leakage.

The next items to be determined are the number of heat exchanger tubes required to remove the excess bed energy. Bed energy removal is a function of excess air, air preheat, coal flowrate and energy/kg, facility heat loss,

TABLE 3-5. DISTRIBUTOR PLATE FLOW RANGE

Plate	Holes/Plate $1935\ cm^2$ Area ($300\ in^2$) n	Holes $1451\ cm^2$ Area ($225\ in^2$) n	Flow Range in dcm^3/min (cfm) for $1451\ cm^2$ at 15°C ($225\ in^2$ at 70°F) 0.996 to 3.98 kPa ΔP (4 in - 16 in)
1	848	632	6797 - 13424 (240 - 474)
2	564	420	4531 - 8921 (160 - 315)
3	376	280	3001 - 5947 (106 - 210)
4	252	160	1727 - 3398 (61 - 120)

energy lost to the offtake ash, energy lost to elutriated solids and the reaction of the sorbent with SO_2. A good approximation, however, can be made by simply considering three of these components miscellaneous and assigning 9376 watts regardless of operating conditions. This reduces the energy equation to:

$$q\ tubes = q\ coal - q\ air - 9376\ watts$$

$$hnA_{tube}\ (t_{bed} - t_{tube}) = \dot{m}_{coal}h_{v} \cdot -\dot{m}_{air}\ (t_{air\ in} - t_{air\ bed}) - 9376$$

$$n = \frac{\dot{m}_{c} \cdot h_{v} - \dot{m}_{air}\ (t_{air\ in} - t_{air\ bed}) - 9376}{h\ a_{tube}\ (t_{bed} - t_{tube})}$$

Some of the values to be used in this equation are still not known accurately since only few test runs have been made. h must be estimated to lie in the range of 255.6 to 368 W/m^2K (Btu/ft^2 - °F-hr), increasing with fluidizing velocity. The area of each cooling tube is equal to 0.0403 m^2 (ft^2) and the maximum t_{tube} should not exceed 93°C (200°F) to prevent boiling. Heat exchangers with five and seven tubes have been provided. Some small adjustment in the heat transfer is possible by varying the water flowrate; however, the principal temperature control of the bed rests with the coal feedrate. After determining how many cooling tubes are required to establish the appropriate test condition, the heat exchangers should be installed in the desired locations.

The remaining ports are available to mount secondary air injection ports and sight or sampling ports.

The air injection ports provide the user with the capability to inject air in the desired location of the combustor or into the freeboard. The secondary air supply panel is very versatile and allows for the insertions of tubes of various lengths at almost any location.

The view and sampling ports are also designed and constructed to provide versatility. Care must be exercised to use them as intended to avoid injury. The panel provides access to the bed or freeboard via a 7.6 cm (3 inch) pipe (SS 330). This pipe can be blocked by a 7.6 (3 inch) slide gate valve to maintain the view glass clear or while installing a sampling adapter. Low pressure purge air (34.5 kPa (5 psi)) may be applied to blow debris from the port through an adapter on the side of the access pipe. Two sizes of view ports are provided, a 3.8 cm (1-1/2 inch) and a 7.6 cm (3 inch) peepsight. The The 3.8 cm (1-1/2 inch peepsight is rated at 689 kPa at 38°C (100 psi at 100°F) and 413 kPa at 204°C (60 psi at 400°F). The large view port is rated for 69 kPa (10 psi). The small peepsight is intended to be used in the bed area whereas the large unit may be used in the freeboard.

All remaining combustor and freeboard ports must be closed by installing a refractory plug and installing a cover plate.

The configuration of the flue gas cleanup devices is prescribed by each test. It is anticipated that the primary cyclone will always be used to accomplish the preliminary collection of particulates. From the primary cyclone the flue gases may be routed to the secondary cyclone via damper control or to the flue gas heat exchanger. The baghouse or the ESP may be connected to the flue gas heat exchanger in parallel or in series. Other control devices can be installed and connected utilizing the supplied flexible ducting. Since the flue gas ducting is under slight positive pressure to expel the gas out of the stack, the configuration of the cleanup devices will change the pressure drop characteristics of this part of the system. For sampling purposes positive pressure is not desirable since the probe entry ports would have to be sealed to reduce the hazard of high-temperature exhaust gases. A damper-controlled stack draft fan may be the ultimate solution to this drawback.

The test plan further calls for the type of coal and sorbent to be used in the FBC Test Rig. These materials must be loaded into their respective feed bins. Both the coal and sorbent must be screened for particles larger than .63 cm (1/4 inch). Loading of the bins is discussed in greater detail in the Solids Feed System Subsection.

Before the system can be started, a bed of fine inert material mixed with 5-10 percent coal must be loaded into the combustor. The material can be either from a previous run or shale of the appropriate size. It can be loaded into the combustor in two modes. Material can be loaded through a sampling port, or it can be fed pneumatically from the third solids feed bin when it is not used to recycle ash from the primary cyclone. The second method has the advantage of being able to raise the bed height faster during startup.

Limestone should not be used to start the bed since it requires a great deal of time to neutralize it and stabilize the reaction after startup.

The system is now ready for startup.

3.1.2 Startup

After the equipment has been prepared, a final visual check should be made of the system to verify the proper test configuration and that everything is properly installed and fastened down. The following described startup sequence can then begin.

Step 1

Close the water system drain valve.

Step 2

Open the main water valves for water supply and discharge. Note the differential pressure on the two local gages. The inlet pressure is typically between 206 kPa (30 psi) and 276 kPa (40 psi) and the discharge pressure between 138 kPa (20 psi) and 172 kPa (25 psi). A minimum differential pressure of 41 to 69 kPa (6 to 10 psi) is required for proper heat exchanger operation.

Step 3

Turn the coolant flow to all heat exchangers off by turning the three-way inlet valves to the vent position. Observe the flow indicator gages on the control console for zero differential pressure. (A pegged gage may indicate air in the instrument line -- bleed the line if this is the case.) The waterflow indication system responds slowly to any flow adjustments and adequate time must be allowed.

Step 4

Check the power circuit breaker panel and insure that all breakers are in the on position for startup.

Step 5

Close the air line valves to the solid feed system (2) and the ash dump valve.

Step 6

Start the air compressor by placing the wall switch in the on position. Observe the air line pressure on the gage mounted on the wall over the blower.

Step 7

Push the power on button on the control console.

Step 8

Open the main air valve located near the blower approximately one turn.

Step 9

Start the blower by pushing the blower-on button and establish a high air flowrate (5664 to 7080 dm^3/min (200 to 250 scfm)) by adjusting the main air valve. (See Figure 3-4.)

Step 10

Check the solid injection tube valve near the combustor to insure it is closed. Turn the baghouse on.

Step 11

Turn power to the main air temperature controllers on. Set the sheath temperature controller to 815°C (1500°F) and the air temperature controller to 538°C (1000°F). "Reset" the controllers by pushing the reset button until the blinking light goes out.

Step 12

Push the heater on power button and hear the contactor close. Observe the temperature rise on the sheath temperature indicator.

Step 13

If no or little bed material is in the combustor, start feeding the material from the small bin by the following procedure.

Step 14

Turn the valves located on the pneumatic control panel for the purge air (V-112) and transport and vibrator air (V-120) on.

Step 15

Set the primary regulator (PCV-118) to 620 kPa (90 psig).

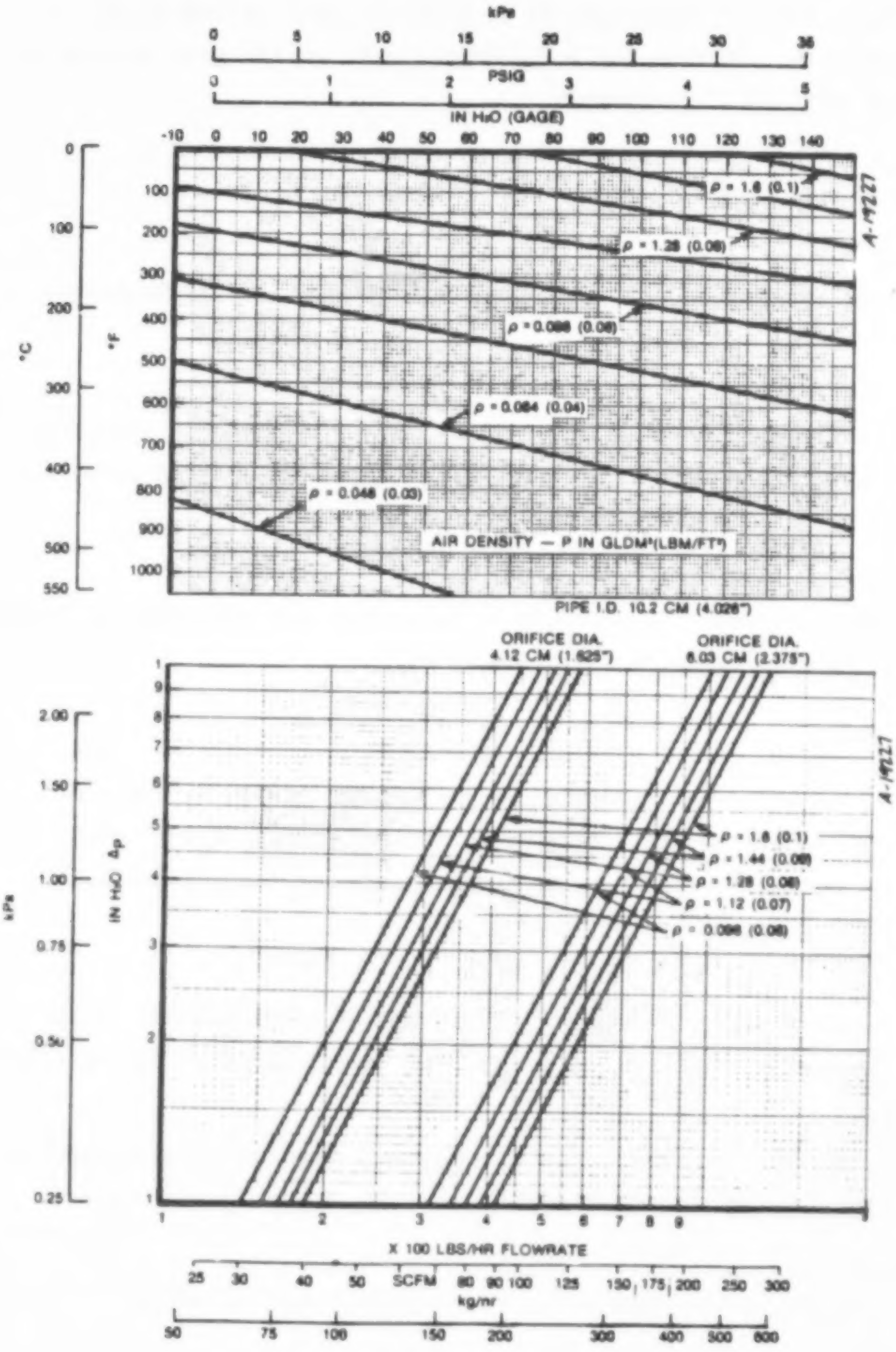


Figure 3-4. Main air flow versus pressure drop.

Step 16

Set the secondary regulator (PCV-119) to 482 kPa (70 psig).

Step 17

Set the purge air regulator to 68 to 136 kPa (10 to 20 psi) and the rotameters to 2.8 sdm^3/min (0.1 scfm) (FI-100, FI-101).

Step 18

Set the ejector inlet regulator (PCV-121) to 13.8 kPa (2 psi).

Step 19

Open the solid injection tube valve near the FBC.

Step 20

Set the ejector air supply regulator (PCV-120) to the required pressure for the needed pressure rise across the ejector. See Figure 2-16.

Step 21

Set the bin vibrator air supply regulator (PCV-117) to $\approx$344 kPa ($\approx$50 psig).

Step 22

Note the loadcell readout in the small bin position. Turn the potentiometer to zero and turn the solids feedrate for the vibrator on. Increase the solids flow and observe the feeding through the sight glass.

Step 23

Stop the feeding of solids when the desired amount is in the combustor.

Step 24

The system has been heating up and will have reached 343 to 371°C (650 to 700°F) in 1 hour sufficient for lightoff. If 5 to 10 percent coal is present in the bed material, lightoff will occur automatically; otherwise coal feed must be started for this to occur.

Step 25

Lightoff can be observed through one of the 3.8 cm (1-1/2 inch) sight ports. Be sure to purge the sight glass with 207 kPa (30 psi) purge air.

Step 26

Open the air shutoff valve to the ash dump valve. Set the upper limit on the bed level control gage.

Step 27

Include the solids feed and check the timing cycles in the back of the control consoles on the bin vibrators. Switch on only those vibrators required.

Step 28

Lightoff results in a rapid increase in the bed temperature observed on the bed temperature probe indicator. A decrease in the airflow will result in faster increases in temperature as well as an increase in coal feed.

Step 29

When the bed reaches 1200°F turn on the water flow to the lowest heat exchanger in the bed. Do this gradually to cool the tubes slowly. Turn on the water flow to the diplegs also. (See Figure 3-5.)

Step 30

Further increase the coal feed and turn on the next heat exchanger, etc.

Step 31

Check the cooler temperature and turn on coolers starting from the top to maintain an outlet temperature of less than 260°C (500°F).

Step 32

Start the sorbent feed.

Step 33

Adjust the coal feed and reduce the air preheat temperature to the desired value.

Step 34

If the bed was low on startup, allow the bed to increase in height growing into the heat exchanger cooling tubes. Further increase the coal feedrate to maintain the temperature of the bed.

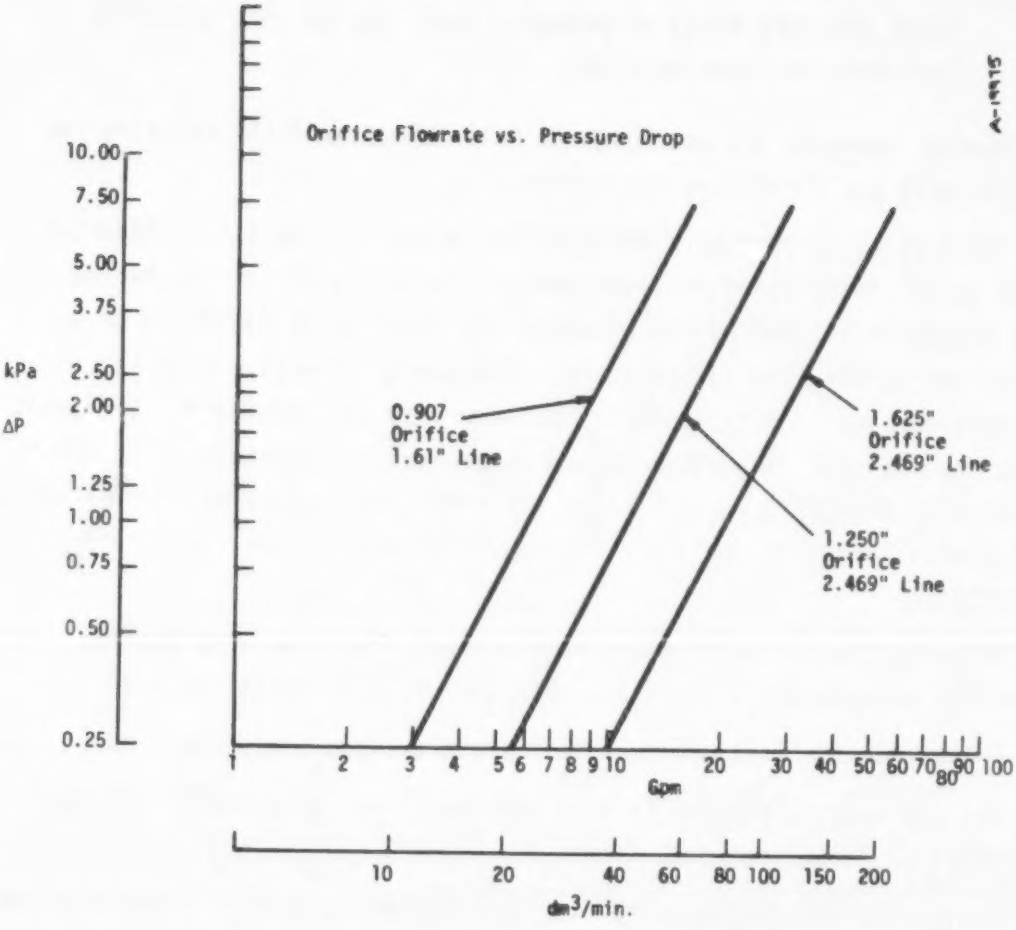


Figure 3-5. Coolant flow versus pressure drop.

Step 35

Adjust the timing cycle on the ash dump valve. Timer one adjusts the buzzer before the valve opens (0 to 5 seconds). Timer two adjusts the closing time after the buzzer starts to operate (0 to 10 seconds) and timer three adjusts the cycle time between actuation (minimum 6 minutes/maximum 60 minutes).

Step 36

Check and make final adjustments until the desired operating condition has been obtained.

Several comments are made here to help in successfully starting the combustion unit and minimizing any damage.

The heat exchangers were designed for water cooling only. Reducing the flow to the flash point is undesirable. Quenching of the bed during startup should be avoided by not allowing the tubes to be submerged or by not establishing any flow in the tubes. The energy removal capability of a submerged exchanger is 4 to 5 times that of one in the freeboard. The tubes are made from SS 310. The tubes should be exposed to temperatures in the 427 to 482°C (800° to 900°F) range for short periods only to prevent sensitization or carbide precipitation to the grain boundary. Higher or lower temperatures are acceptable.

Prolonged operation of the blower without flow should be avoided. It is therefore recommended to open the main air valve at least one turn.

The air heater will not operate without a certain minimum flow.

The ash recycle bin may be used to store inert material if ash feed is not required for a test condition.

During startup the pressure drop across the distributor plate will be exceptionally high and particularly with high preheat temperatures. This is normal. Fluidization of the bed is also not likely to occur until a minimum fluidization velocity with increasing temperature has been achieved.

Until lightoff has occurred it is suggested to operate the unit adiabatically as much as possible — no heat exchanger surface submerged. The unit should be brought on line gradually to minimize damage to the refractory.

The baghouse should be bypassed until the exhaust gas temperature is high enough to prevent condensation (122°C (252°F)). This is not necessary with preheated air.

The method suggested to start the combustion has been successfully employed but requires many adjustments before the final operating condition can be acquired. Large volumes of preheated air would be required to speed up this process or to withdraw heat at the same time via heat exchanger. Should it not be possible to start the combustion in the outlined fashion due to a particular test configuration, a lit butane or natural gas lance may be inserted in the lower portion of the bed for the additional energy required.

3.1.3 Shutdown

Shutdown of the system is extremely simple. The only concerns rest with the protection of the refractory components and minimizing thermal shock. The steps to be followed are the following:

Step 1

Reduce the coal feed rate gradually and reduce the temperature of the combustor to ≈425°C (≈800°F).

Step 2

Discontinue coal and sorbent feed.

Step 3

Cool the unit further with air, minimizing thermal shock for refractory protection.

Step 4

If the heater was on, turn if off.

Step 5

Turn all heat exchanger coolant flows off and vent the heat exchangers.

Step 6

Turn the air supply to the dump valve off.

Step 7

When the combustor has cooled to 600°F, turn the blower off.

Step 8

Adjust the ejector air supply pressure to zero and close the solids feed line valve.

Step 9

Turn the transport vibrator air and purge air valves to off.

Step 10

Turn the control console power off.

Step 11

Close the main water valves and open the drain valve.

Step 12

Turn the circuit breakers on the power panel to off.

Operator judgement should be used in the speed with which the system is shut down. Fast shutdown will result in higher refractor repair requirements.

The facility is equipped with a number of safety interlocks designed either to warn the operator or to automatically shut off subsystems. The control console power-off knob will shut down all electrically controlled systems, principally the solids feed system, the air preheater, the blower, the baghouse and the ESP. The severity of the malfunction of course dictates the action. To prevent slug formation the bed will be dumped when the air flow is too low for fluidization or upon a power failure.

3.2 COMBUSTOR OPERATION

The combustor itself is primarily a passive element although it houses the combustion. Few controls are located on or near the combustor. The following paragraph will therefore describe the expected conditions of normal operation of its components.

Combustor and Freeboard Sections

The combustion chamber is refractory lined and sensitive to high-temperature fluctuations over short periods of time. To minimize thermal shock, one to two hours are required for warmup and cooldown. The expected surface temperature of the combustion chamber at 900°C (1650°F) operating combustion temperature is 100°C (212°F).

During the operation the combustor is under positive pressure. The extent of pressurization depends on the flowrates and the gas cleanup system configuration. This feature, however, requires frequent verification that packings and seals on the combustor are airtight. Small leaks tend to grow larger because they cause high-temperature gases to pass to the combustor shell and cause seal erosion.

Distributor Plate

The distributor plate pressure drop should be approximately 30 percent of the bed pressure drop. The combustor has been designed to accommodate a maximum 122 cm (48 inch) bed depth and 0.8 kg/dm^3 (50 lbm/ft^3) solids density this results in a maximum 4.5 kPa (18 inch H_2O) pressure drop requirement for the distributor plate. Solid to fluidized bed expansion is assumed to be $\approx 1:2$. The operation of the distributor plate must be anticipated to allow the proper selection. The distributor plate operates near the bed operating temperature and could experience two modes of failure: plugging or breakthrough. Both failure modes can be detected by the change in pressure drop across the plate. A higher than normal pressure drop indicates plugging and a lower than normal pressure drop breakthrough. Both failure modes require the shutdown of the facility and correction of the problem.

The distributor plate can be operated at a lower temperature by introducing a layer of large inert pebbles (0.95 cm (3/8 inch) in diameter) into the bed. This layer of pebbles (2.5 to 7.5 cm (1 to 3 inches) thick) acts as an effective insulation layer in which little combustion takes place. This may be a desirable mode of operation for some high-temperature tests. Rapid corrosion rates have been witnessed for material temperatures above $900^{\circ}C$ ($1650^{\circ}F$) resulting in damage to the distributor at other facilities.

Heat Exchangers

Two types of heat exchangers are provided for the combustion section -- five and seven tube modules. The heat exchangers can be inserted in the desired location of the bed. The design requires that they be operated in the liquid coolant phase. Flashing can be prevented by establishing a minimum heat exchanger tube flow of 2.7 kg/min (6 lbm/min). A five-tube bundle therefore requires 13.5 kg/min (30 lbm/min) and a seven-tube bundle 32.6 kg/min (42 lbm/min) minimum flow.

Each heat exchanger outlet is equipped with a thermocouple. Should the outlet temperature of a heat exchanger exceed 82°C (180°F), the flowrate should be increased. The bulk water outlet temperature should not exceed 60°C (140°F) to protect the cooling tower. An alarm light will indicate the overtemperature condition and cause the solids flow to be discontinued.

Flowrates to the heat exchangers can be controlled by two control valves across two orifices of low and high flow capacity. For low flow requirements the 3.8 cm (1-1/2 inch) diameter Schedule 40 line is equipped with a 2.30 cm (0.907 inch) diameter orifice plate. The 6.35 cm (2-1/2 inch) diameter Schedule 40 line is equipped with a 3.27 cm (1.250 inch) diameter orifice. A spare 4.13 cm (1.625 inch) diameter orifice for higher flow capabilities for a 7.5 kPa (30 inch) H_2O pressure differential has been delivered. Flow characteristics are shown in Figure 3-4. These curves apply to the combustor coolant flow circuits as well as the flue gas coolant circuits. These curves are generated from the general orifice equation

$$\omega = KaYFa \sqrt{2g_c \, (\Delta p) \, \rho}$$

where

$$K = 0.5930 + 0.4\beta^4 + (0.0015\sqrt{\beta} + 0.012\beta^4)\frac{1000}{\sqrt{R_D}}$$

ω = gravimetric flowrate
K = orifice coefficient
a = orifice area
Y = expansion factor
Fa = coefficient for thermal expansion of the orifice plate
g_c = scaling factor
Δp = differential pressure across the orifice
ρ = density as a function of temperature
β = diameter ratio
R_D = Reynolds number

When a heat exchanger is mounted in the combustor but has no established coolant flow it must be vented to the drain. This is done automatically when the three-way valve is turned to close the flow off. It is important, however, to turn the valve handle completely so as not to block flow in both directions. The drain hose to the drain header must also be secured and all open drain openings plugged to prevent splashing.

Bed Height and Temperature Sensors

Pressure and temperature measurements are made in various locations of the combustion and freeboard sections. All thermocouples are Type K, whereas the temperature switches are of the capillary type. The pneumatic signal lines may plug on occasions and may have to be cleared by purging. Pressure measurements are made with magnehelic gages that require little maintenance. To insure accuracy of the measurements, the "zeros" should be checked before a run.

Sampling, View, and Secondary Air Ports

The sampling and view ports can be mounted in the unused access ports of the combustion or freeboard sections. The 7.62 cm (3 inch) peepsights are intended for use in the freeboard area where the 3.81 cm (1-1/2 inch) units are to be used in the fluidized bed region. Care must be used to apply safe purge air pressures to these ports while the slide gate valve is closed. The large units are rated for 69 kPa (10 psi) purge air whereas the small units may be used with up to 689 kPa at 38°C (100 psi at 100°F) and 413 kPa at 204°C (60 psi at 400°F). A regulator with adjustment capability up to 413 kPa (60 psi), hose, quick connects and shutoff valves is provided.

Secondary air ports are provided that allow injection of air into the fluidized bed or into the freeboard region. Flexible metallic hoses connect to these ports and essentially allow the bypass of the distributor plate. The operation and control of the air quantities is discussed in the section for the air system.

Ash Removal System

The bed height is controlled by removing excess quantities of bed material through the 5.08 cm (2 inch) diameter ash dump pipe located in the center of the distributor.

Bed height is measured by noting the pressure differential between three known points — two in the bed region and one in the freeboard. The bed density is measured by noting the pressure differential between two points, a known distance apart within the bed, and the bed height by proportion to the third port. The bed density measurement is made and indicated by gage DP1-107. The connection of the pressure tabs should be verified at the time of the test to insure reliable bed height data.

The bed height is indicated by Photohelic gage DP1-106. The Photohelic gage controls a solenoid valve between two manually adjustable setpoints that direct the opening or closing of the bed dump valve. The upper setpoint needle triggers a timing circuit that will sound an alarm, open the valve for up to 10 seconds and limit the dumping of bed material to once every 6 to 60 minutes. The duration of the alarm, opening and closing of the valve and the repeat cycle are independently variable. This feature allows the automatic bed height control of the fluidized bed within a very close tolerance band.

3.3 AIR SYSTEM OPERATION

The air system supplies the required combustion air to the combustor at the various desirable locations at the desired preheat temperature. It is also possible to recirculate up to 25 percent of the flue gas for flue gas recirculation. The prime gas mover is a Spencer turbine blower. The system is easy to understand and operate. The flow is controlled by manual valves at the various strategic locations. Flow measurements are indicated by pressure and temperature measurements across orifices. Figures 3-5, 3-6 and 3-7 show the flowrates for a number of limited cases. The general orifice equation shown in Section 3.2 should be used to compute the accurate flow measurement for the specific desired operating condition.

The various air supply lines have been equipped with orifices of the following indicated sizes. Several plates have been provided for some lines for high and low flow capabilities.

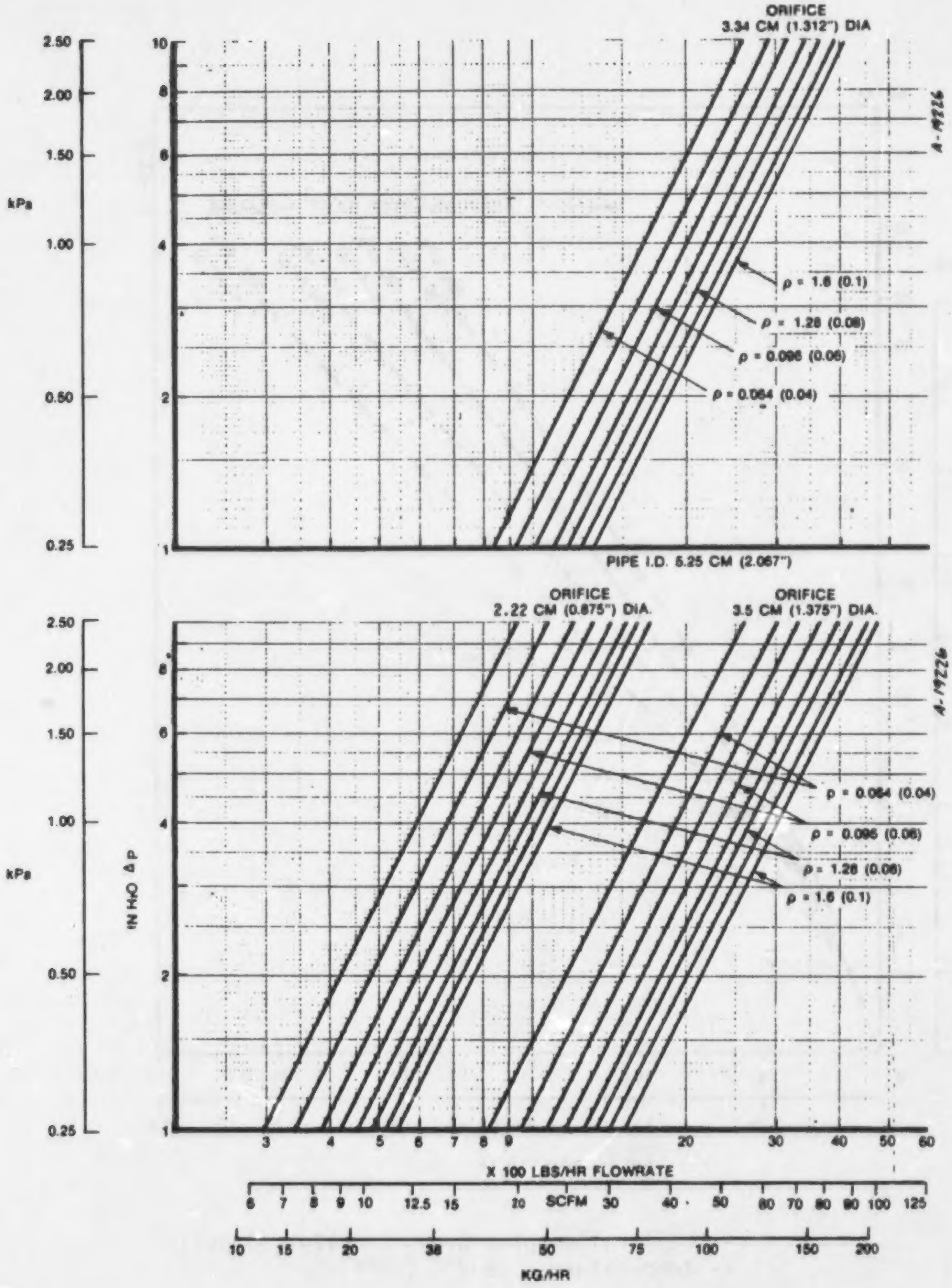
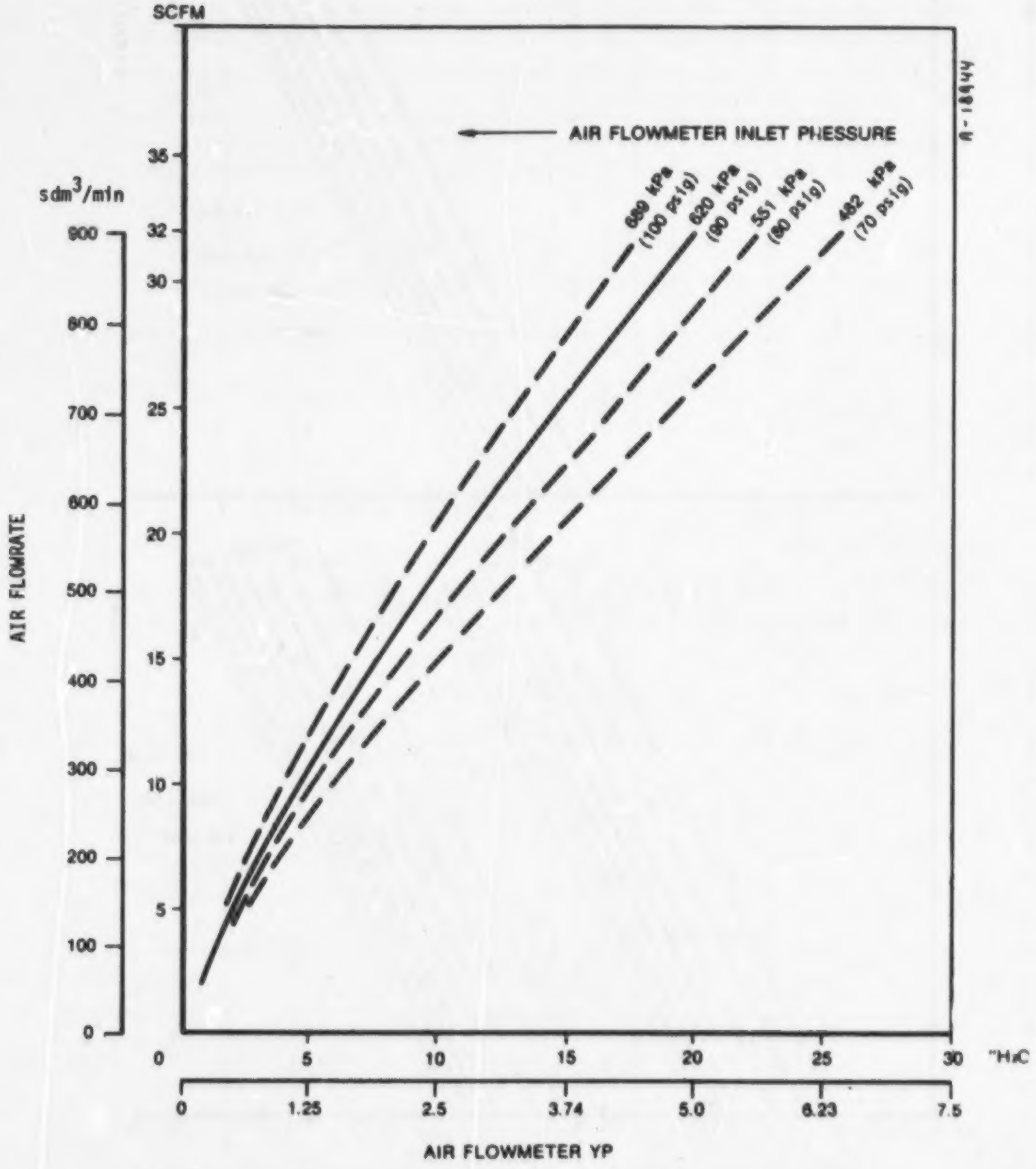


Figure 3-6. Secondary air and FGR versus pressure drop.



-- calibration pressure: 620 kPa (90 psi)
-- temperature: 26.7°C (80°F)

Figure 3-7. Air flowmeter ΔP versus sdm^3/min (scfm)

Measurement	Pipe Size Schedule 40	Orifice Size cm (in)
Main air	10.2 cm (4")	6.03 (2.375)
Main air	10.2 cm (4")	4.13 (1.625)
Flue gas	5.1 cm (2")	3.33 (1.312)
Secondary air	5.1 cm (2")	3.50 (1.375)
Secondary air	5.1 cm (2")	2.22 (0.875)

The measured pressure differentials are indicated on the control console by the appropriate gages.

Startup

Step 1

Open the mixing chamber valve.

Step 2

Open the main air valve one turn.

Step 3

Supply power to the control console.

Step 4

Push the blower start button.

Step 5

Adjust the main flow to the desired flowrate.

Step 6

Set the heater controllers to the desired air temperature. Check the sheath temperature controller for proper setting.

Step 7

Apply power to the heater by turning the heater power switch on.

Step 8

Observe the air temperature indication. To establish a secondary air flow do the following.

Step 9

Insure the flexible air duct is connected to the air port and open the appropriate valve slowly. Opening the valve too far may result in the loss of fluidization due to the loss of head at the distributor plate.

Step 10

For secondary temperature control, adjust the two mixing valves. If more back pressure is required, throttle the flow with the 10.2 cm (4 inch) valve before the air plenum.

Step 11

Adjust the total flow to compensate for pressure and temperature changes.

Step 12

Flue gas recirculation is established by opening the 5.1 cm (2 inch) FGR line valve.

Step 13

Slowly close the mixing chamber 10.2 cm (4 inch) valve until the desired flowrate is established through the FGR line.

Shutdown

Turn the heater and blower power off.

The air system has a number of safety interlocks that protect it from damage and furthermore require the startup sequence to be followed. The blower is rated for 7080 sdm^3/min (250 scfm) and a pressure rise of 34.5 kPa (5 psi) at up to 93°C (200°F) inlet temperatures. The blower will shut off if this temperature is exceeded. If the flowrate is exceeded the blower will thermally overload the motor and shutdown will also occur. To keep the blower from surging the flow should never be blocked completely. This is why it was recommended to crack the main air valve one turn.

The heater is protected by two interlocks. Low air flow and high heater sheath temperature will both cause the heater to cut out.

The interlock sensors should be checked periodically to insure that they indeed supply the expected protection. Adjustments requirements are discussed in the component literature.

Service of the air system components is minimal. The blower needs to be lubricated periodically as outlined in the Spencer service manual and the Demister screen and inlet filter should be cleaned as required.

3.4 SOLID FEED SYSTEM

The solid feed system has been designed and constructed to meet the required performance characteristics listed in Table 3-6.

Section 3.4.1 describes safety considerations, bin loading, startup, steady-state operation, shutdown and bin unloading. Calibration and setup of the load cells, flowmeters, feeders, relief valves and timer is discussed in Section 3.4.2.

3.4.1 Safety Considerations

The safety precautions necessary to operate the solid feed system are minimal and straightforward.

The most important safety precaution is to verify the operation and adjustment of the two pressure relief valves. Adjustment of these valves is covered in Section 3.4.2.

Another necessary safety precaution is to insure that everything is tight and in place, insure that the plexiglass viewport has been uniformly tightened down, and that the handrails are installed and bolted securely.

Bin Loading

The bins can be loaded in one of two modes. They can be loaded with the solid feed system operating, or without. The actual loading procedure is identical except for one additional step if the system is operating.

During operation of the system, it is necessary to reduce the bin pressure to atmospheric pressure. To do this it is necessary to have at least 566 sdm^3/min (20 scfm) of transport (primary) air flow. If it is necessary to increase the transport air flow, total combustion air can be maintained (if desired) by decreasing the fluidization or secondary air. To reduce the bin pressure to atmospheric conditions, increase supply air (with the supply air regulator on the local control console) to the value shown in Figure 2-16 corresponding to the existing FBC inlet pressure and to zero inlet air pressure. Following, reduce the inlet air flow to zero (with the inlet air regulator on the local control console). It may be necessary to readjust the supply air now to achieve atmospheric pressure in the bin.

TABLE 3-6. SOLIDS FEED SYSTEM SPECIFICATIONS

Dust Feedrates		
Coal	10 - 50 kg/hr (22 - 110 lb/hr)	
Sorbent	0 - 25 kg/hr (0 - 50 lbs/hr)	
Ash	0 - 9 kg/hr (0 - 20 lbs/hr)	
Particle Size	0.63 cm (to 1/4") (max dia)	
Bin Capacity		
Coal	935 dm^3 (33 cu ft)	
Sorbent	396 dm^3 (14 cu ft)	
Ash	198 dm^3 (7 cu ft)	
Run Time (at max. flowrate)		
Coal (at 50 kg/hr)	15 hrs. - assumes:	0.80 kg/dm^3 (50 lbs/ft^3)
Sorbent	21 hrs. - assumes:	1.2 kg/dm^3 (75 lbs/ft^3)
Ash	12 hrs. - assumes:	0.56 kg/dm^3 (35 lbs/ft^3)
Air Flowrate	to 906 sdm^3/min (32 scfm)	
Air/Fuel Ratio	from 1.25 kg (lb) air/kg (lb) solids	

Example: Given the following conditions —

- FBC inlet pressure — 11.2 kPa (45 in WG)
- Air supply pressure — 68.9 kPag (10 psig)
- Inlet supply pressure — 34.5 kPag (5 psig)

This would correspond to approximately 396 sdm^3/min (14 scfm) air flowrate and 9.2 kPa (+37 inch WG) bin pressure. To load the bins, it is necessary to increase the air flowrate to 736 sdm^3/min (26 scfm) which corresponds to approximately 503 kPa (73 psi) supply air pressure and zero inlet air.

Actual loading details are simple. Remove the lid(s) or cap(s), attach the funnel and add material. Make absolutely sure that the maximum particle size is not in excess of 0.64 cm (1/4 inch) (maximum dimension). It is easier to screen the material before loading. Replace lid(s) or cap(s) and tighten uniformly.

Startup

Using Figure 2-16, pick a set of air inlet and supply pressures that satisfy the air flowrate requirement. It is usually to advantage to run as much inlet air as possible, but some supply air should be used to avoid getting dust into that section of tubing.

- With the FBC inlet valve closed, turn on the air and set the desired inlet and supply pressures (on the local control console).
- As the bin pressure reaches 12.45 to 14.94 kPa (50 to 60 inch WG), open the FBC inlet valve
- Set the purge air (on the local control console) to approximately 2.8 sdm^3/min (0.1 scfm)
- Set each solids feedrate to the desired level. Refer to Section 3.4.2 for calibration procedures.
- Turn on flyash vibrators. Also turn on coal and sorbent vibrators if either bin is near empty.
- Recheck and fine-tune the air flowrate using Figure 3-7 and the flowmeter gages on the remote control console.

- Fine-tune the solids feedrate by monitoring the loadcell readout of each. The potentiometers have been equipped with a range control that can be adjusted from the back.

Steady-State Operation

Duties required for steady-state operation are minimal. They are:

- Solids feedrate adjustment and monitoring — feedrate is computed by noting the change in loadcell reading over a known time span. However, it must be noted that the vibrators, or changes in bin pressure, may have a slight effect on the loadcell reading. It is best (most accurate) to take readings at an arbitrary condition, e.g., take reading with the vibrators on, and with a bin pressure of 7.5 kPa (+30 inch WG). It is possible to maintain a given bin pressure while changing air flowrate or FBC bed height by changing the ratio of inlet air pressure to supply air pressure. Consult Figure 2-16 for this information.
- Air flowrate adjustment and monitoring — air flowrate is computed from flowmeter inlet pressure and differential pressure information (from the remote control console), and the flowmeter calibration curves shown in Figure 3-7. Temperature corrections can be made by multiplying the flowrate given in the figure by the ratio of the calibration temperature 26.7°C (80°F) to the actual temperature (in absolute units).
- Loading — three indicator lights on the remote control console indicate when each of the bins are getting empty. Loading instructions are given in this section to assure leak-tight operation.

When the air-flow ratio (between inlet air and supply air) is varied it is important to maintain the air flow in the transport line (to avoid clogging).

Bin Unloading

To unload the dust from each bin, it is necessary to open the unloading port (7.6 cm (3 inch) pipe plug) at the bottom of each cone, and let the material fall along a chute, tray, or tube into a drum or barrel. The plug can be easily replaced even with the bin partially full.

Shutdown

Shutdown of the solids feed system is accomplished in the reverse order of startup:

- Turn off bin vibrators
- Turn off vibratory feeders
- Shut FBC inlet valve
- Shut off purge air
- Shut off transport air

3.4.2 Solid Feed System Calibration and Setup

This section covers the adjustment and/or calibration of all of the applicable devices in the solids feed system. Some devices like the flowmeter and the loadcells need to be (or have been) calibrated only once. Others like the feeders and vibrator timers change their characteristics with any material change, and may have to be readjusted or recalibrated. The pressure relief valve should be checked periodically and readjusted if necessary.

Loadcells

Raw output from the loadcell is conditioned by an Action-Pak Model AP 4051 signal conditioner (located in the back of the control console). The Action-Pak unit is equipped with an adjustable span and zero. This conveniently makes it possible to subtract the weight of the empty bin from the total weight and indicate only the material.

- Set the zero value with each bin completely empty (with the lids and lid bolts on). Make sure that the internal gage pressure in the bin is zero, as this has a slight effect on the reading. If the bin weight cannot be completely eliminated because the zero adjustment is not sufficient, choose a value of 100, 1000, or some other convenient number.

- To set the span, add a known weight of dust to each bin and adjust the span to read this value. It is possible that the span adjustment will not have the range to reach the required value. For this case it is necessary to increase or decrease the amount of excitation of the signal conditioner. This adjustment is also on the Action-Pak module. If the excitation is changed, it is necessary to repeat the zeroing procedure above.

The loadcell readout can be calibrated in virtually any units. It must be noted, however, that the decimal point is not shown. For example, a flyash readout of 1456 is actually 145.6 lbs. The coal and sorbent, however, have the decimal at the extreme right.

The limit alarms, used to indicate a low bin-level condition in any bin, are Action-Pak Model 1020's. These are also located in the back of the control console. The easiest way to adjust these units is to add the amount of material that represents a near-empty condition, and adjust the Action-Pak module until the indicator light turns on. An alternate method is to apply an adjustable voltage to the input of the signal conditioner to represent a loadcell output.

Recommended level alarms are:

- Coal bin -- 50 kg (110 lbs)
- Sorbent bin -- 22.6 kg (50 lbs)
- Ash bin -- 9.06 kg (20 lbs)

These loads give a 1-hour warning to the operator.

Flowmeter

The flowmeter, a Meriam Model 50MJ10 laminar flow element, has been calibrated in its present configuration. The calibration was done at 620 kPa (90 psig) and 26°C (80°F) inlet conditions. The calibration curve is shown in Figure 3-7. Flowrates for other inlet pressures have also been calculated and plotted on the figure.

Temperature corrections, as explained in Section 3.4.1, can be made by multiplying the value obtained in Figure 3-7 by the ratio of the calibration temperature (26.6°C (80°F)) to the actual temperature using absolute temperature units.

Feeders and Feed Nozzles

To determine initial solids feedrate settings, it is necessary to have at least a rough calibration of feeder performance. Since solids feedrates are dependent on material characteristics (density, particle size distribution, etc.) it is necessary to recalibrate it for every change in dust characteristics.

Calibration of the feeders is a simple matter. Feedrate is not a function of bin pressure or air flowrate. The transport line can be removed and the dust fed directly into a bucket for subsequent weighing.

If it should be necessary to change the characteristics of the feedrate curves (either because the feeder does not feed fast enough, or because the feedrate control is too sensitive), some methods are:

- Nozzle height – the clearance between the feed nozzle and the feeder tray can be varied to increase or decrease the maximum solids feedrate. The larger the clearance is, the larger the pile of material on the tray will be, and hence the higher the maximum feedrate will be. However, as the pile gets larger, the flow quality goes down.
- Nozzle gate position – nozzle gate position has the same effect on feedrate and flow quality as nozzle position. It has the additional drawback of increasing the likelihood of clogging in the low position.
- Feeder tray inclination – as the feeder tray inclination increases, so does the feedrate and flow quality. The limiting factor is purely physical interference with the feed nozzle and with the mixing cone. The feeder tray inclination is varied by changing the standoff height of the feeder mount. If the feeder tray inclination is changed, insure that the standoff-box interface is airtight.

Feeder performance is optimized when the maximum design feedrate is at roughly 90 to 95 percent actual maximum. The nozzle gate should be as much open as possible, the nozzle as low as possible, and the feeder tray inclination as steep as necessary.

Relief Valves

To keep the bins from ever being pressurized to more than 34.5 kPa (5 psig), two redundant pressure relief valves are included in the solids feed system.

The pressure relief valves are adjustable within certain limits. They must be checked and adjusted at frequent intervals to assure safe operation of the system.

The relief pressure is set by adjusting the preload on the spring inside the valve; higher preload results in a higher relief pressure.

The following steps outline the procedure used in setting the relief pressure.

Step 1

Set the spring preload to the minimum value.

Step 2

Pressurize the relief valve, and note the relief pressure.

Step 3

If the relief pressure is less than the desired value, increase the spring preload by a small amount. Repeat Steps 2 and 3 until the relief pressure is at the desired level.

Vibrator Timers

The vibrator timers are located in the back of the control console. They are adjustable for both on-time and off-time. Suggested setpoints are given in Table 3-7 but, because dust-flow characteristics are so variable, the final setpoints must be determined by experience.

TABLE 3-7. SUGGESTED VIBRATOR TIMER SETPOINTS

	On Time (seconds)	Off Time
Coal Bin (Cone Vibrator)	30*	3
Sorbent Bin (Cone Vibrator)	30*	3
Ash Bin (Cone Vibrator)	10	5
(Down-Comer Vibrator)	10	20

---

*Coal and sorbent should have to be turned on only when the bins are nearly empty.

Vibrator timing should be set to run as little as possible while continuing to give satisfactory performance. There are two reasons for this: first, it will minimize the air consumption, and second, it will also minimize the chance of packing or segregating of any of the materials.

3.5 GAS CLEANUP SYSTEM OPERATION

The gas cleanup system can be classified into two sections. The high-temperature sections employ two cyclones for particulate control and the low- (260°C (500°F)) temperature cleanup section a baghouse and an electrostatic precipitator. Operation of these devices is outlined in the following subsections.

Primary Cyclone

The primary cyclone is a rather passive element once the basic configuration has been established. This particular unit is equipped with a SS 310 outlet tube insert that may be changed to slightly alter its performance characteristics and pressure drops.

The dipleg is equipped with a water jacket that can be utilized should the amount of solids collected require active energy removal. A manual valve controls the flow to this jacket. Care must be exercised to prevent condensation in the dipleg and cause problems such as plugging due to wet particulate.

The ash container can be isolated by a slide-gate valve and emptied during operation.

"Tornado" Cyclone

The secondary cyclone differs from the primary cyclone in its construction and has a reported higher collection efficiency for fine particulates. The body of the cyclone, rather than being refractory lined, is of SS 310 and externally insulated. This construction method allows operation to 927°C (1700°F) unless very high corrosion and erosion rates are acceptable. Operations that encounter higher flue gas temperatures should bypass this unit. The cyclone can be bypassed by opening the main damper valve in the flue gas duct and closing the inlets to the cyclone.

To operate the unit, flow adjustments have to be made to cause the pressure drop between the secondary inlet and outlet duct to be 2.25 kPa (9 inch H_2O) differential pressure. This establishes the required vortex in the cyclone. The remaining flow is then introduced into the primary inlet.

The pressure and temperature measurements are indicated on the control console.

The dipleg configuration and service requirement are the same as those for the primary cyclone.

Electrostatic Precipitator

The service and operation requirements of the electrostatic precipitator are minimal. To operate the unit the inlet and outlet duct has to be connected and power applied to the unit from the control unit.

The plates of the ESP should be inspected after each run to insure that they are clean and the bottom trap should be emptied.

Baghouse

The baghouse, a Young Model VM42-16, also requires very little service and operating expertise. The hoses have to be connected and power and air have to be supplied.

The dust collected in the bags is discharged into a 208 dm^3 (55 gallon) drum through a slide-gate valve. The drum can be exchanged during operation with this feature.

The teflon bags supplied with the unit are rated for up to 232°C (450°F) operation. An overtemperature and overpressure sensor indicate and warn the operator if the maximum ratings are exceeded so that they can be corrected.

The equipment is further described in the manufacturer's literature.

The flue-gas ducting can be rerouted to permit the reconfiguration of the facility to meet the needs of the test program.

3.6 FLUE-GAS HEAT EXCHANGER AND SOOT-BLOWING LANCE OPERATION

The flue-gas heat exchanger's function is to cool the flue gases to 149 to 204°C (300°F to 400°F). The inlet gas temperatures may vary substantially as well as the flowrates and a very high turndown ratio is required to accomplish this. This flue-gas heat exchanger contains 10 heat exchanger modules that can be individually brought on line. The design parallels that for the fluidized bed combustor with the exception that these heat exchanger modules always remain mounted. Flue gases are cooled as they pass through the maze of bare tube from the top down. The operation of the heat exchanger requires, therefore, that 10 heat exchangers be brought on line in sequence from the top until the desired exit temperature is achieved. The bare tube design allows for particles to be removed from the tubes by soot blowing. Coolant outlet temperatures can be monitored on all modules and one measurement provides a bulk outlet temperature measurement. A second outlet temperature sensor provides an alarm status light if the bulk temperature rises above 60°C (140°F).

Coolant water flowrates are monitored by measuring orifice differential pressure drops in the same fashion as for the fluidized bed. Since the heat transfer coefficients are substantially lower here than in the bed, flashing is not likely to be a severe problem. Flowrates can therefore be kept substantially lower than in the combustor bed. Each tube has a heat transfer area of 0.060 m^2 (0.64 ft^2). The top base modules have five heat transfer tubes whereas the remaining eight have nine tubes. Due to the highly varying flue gas flowrates the outside heat transfer varies substantially. A 1.8 kg/tube (four-lbm/tube) flowrate appears to be sufficient to limit the temperature rise to acceptable limits. Figure 3-4 may be used to set the flowrates. Verifications of the outlet temperature will confirm the requirement.

The flue gas contains particulate in the 5μ-or-less category. Some of this ash will deposit on the tubes and needs to be cleaned off periodically. A manually operated soot-blowing lance can be inserted above and below the bare tube heat exchangers. This task can be done while the unit is operating or when it is shut down. An air jet is directed at the tubes cleaning them as the lance is moved in and out. The dust settles in the bottom ash pan or is carried into the baghouse or ESP. The ash pan can only be removed after a run has been completed. Large dust accumulations on the tubes would indicate ineffective heat transfer or a rise in the flue gas cooler outlet temperature for no other apparent reason.

3.7 EMERGENCY SHUTDOWN

Should it ever become necessary to shut the system down due to an emergency, the following control options exist.

All electrical power to the system is cut off by pushing the control console power-off button. Coolant flow and the pneumatic transport air will continue until shut off separately. If the failure is not due to a heat exchanger tube failure it will be desirable to continue the coolant flow to reduce the system temperature as quickly as possible.

To turn off the coolant flow and solid transport air flow close the respective main valves.

When the power to the system is cut off the bed will be dumped.

SECTION 4

FBC TEST RIG SAMPLING AND ANALYSIS

This section specifies the sampling and analysis techniques recommended for application to the subscale fluidized bed coal combustion (FBC) test rig. Many of the techniques and specific equipment suggested represent "state of the art." That equipment which does not represent state of the art, has been chosen to meet EPA's requirements of utility, convenience, minimal expense and ease of operation. However, all decisions were based on the following criteria:

- Flexibility for a wide range of operating variables and equipment configurations
- Accuracy
- Utility to minimize EPA manpower requirements

Certain "ground rules" were laid down by EPA with regard to the sampling and analytical equipment. First, all analysis (with the exception of online analysis instrumentation) is to be accomplished offsite. Second, online analysis instruments are to be strictly limited to those that are commonly available and straightforward in operation. More complex measurements, such as those involving mass spectrometry or gas chromatography, are required to be done offsite.

These ground rules have been strictly adhered to. Included in this report is a tabulation of recommended analytical labs (Table 4-1)

TABLE 4-1. SAMPLING SERVICES CONTRACTORS

Contractor	Home Location	Nearest Office
Acurex Corporation/ Aerotherm Division	Mountain View, CA	RTP, NC
Battelle Memorial Institute	Columbus, OH	OH
BETZ Environmental Eng.	Plymouth Meeting, PA	PA
George D. Clayton & Associates	Southfield, MI	MI
Commonwealth Laboratory, Inc.	Richmond, VA	Greenville, SC
Engineering Science, Inc.	McLean, VA	VA
Enthopy Environmentalists	RTP, NC	RTP, NC
Environmental Science and Engineering	Gainesville, FA	FA
Gilbert Associates	Philadelphia, PA	PA
Midwest Research Institute	Kansas City, MO	MO
Monsanto Research Corporation	Dayton, OH	RTP, NC
Pacific Environmental Services	Santa Monica, CA	CA
Rossnagel Associates	Cherry Hill, NJ	GA
Scott Research Laboratory	Plumbsteadville, PA	PA
TRW Systems Group	Los Angeles, CA	CA
York Research Corporation	Stamford, CT	CT

including both institutional and private laboratories. Also included (Table 4-2) is a list of recommended source sampling companies which could provide support for the FBC test rig experiments. As a further aid the APCA 1976 Consultant Guide, published in the APCA (Air Pollution Control Association) Journal in July 1976, may be consulted.

The onsite sampling and analytical instruments chosen are capable of continuously monitoring such pollutants as SO_2, NO, NO_x, CO, CO_2, O_2, low molecular weight reduced sulfur compounds, and light hydrocarbons (C_1 to C_6). Onsite continuous monitoring instrumentation for the collection and analysis of low molecular weight reduced sulfur compounds (H_2S, RSH, RSR, etc.) is essential due to the high reactivity of these species. This mode of analysis eliminates the transportation of a large number of bulky samples and permits additional sample analysis if problem areas become apparent during initial sampling.

The vast number of chemical and physical pollutant forms of interest (Table 4-3 in Attachment No. 1 in the RFP) are impractical to consider individually. Furthermore, many of them may be grouped and considered as one species due to their similarity with regard to sampling and/or analytical technique. Therefore, a pollutant species grouping approach has been taken in this portion of the report. This approach does not, however, preclude analysis for specific components. Table 4-4 is a complete summary of sampling and analytical methods recommended for use with the FBC test rig. Figure 4-1 is a flow diagram of the proposed FBC test rig showing all sampling locations. Table 4-5 relates the sample locations to their general sampling requirements. The gaseous and particulate sample requirements referred to in Table 4-4 will be

TABLE 4-2. POTENTIAL ANALYTICAL CONTRACTORS

Laboratory	Location
Battelle Memorial Institute	Columbus, OH
Commonwealth Laboratory, Inc.	Richmond, VA
Dow Chemical Interpretime Analytical Services	Midland, MI
Environmental Services Associates, Inc.	Burlington, MA
Galbraith Microanalytical Laboratories	Knoxville, TN
Gilbert Associates	Philadelphia, PA
Gulf Energy and Environmental Systems	San Diego, CA
LFE Environmental Analysis Laboratories	Oakland, CA
Langston Laboratories	Kansas City, MO
Arthur D. Little	Boston, MA
Midwest Research Institute	Kansas City, MO
Monsanto Research Corporation	Dayton, OH
Research Triangle Institute	RTP, NC
Southern Research Institute	Birmingham, AL
Southwest Research Institute	San Antonio, TX
Stanford Research Institute	Palo Alto, CA
TRW Systems Group	Los Angeles, CA

TABLE 4-3. EXAMPLE LIST OF CHEMICAL AND PHYSICAL FORMS OF POLLUTANTS OF CONCERN: POLLUTANT CHEMICAL FORMS

Sulfur Compounds

- Elemental sulfur
- Oxidized (sulfur dioxide, sulfur trioxide, sulfites, sulfates)
- Reduced (hydrogen sulfide, carbonyl sulfide, sulfides, disulfites)

Nitrogen Compounds

- Oxidized (nitric oxide, nitrogen dioxide, nitrates, nitrites)
- Reduced (ammonia, cyanides, cyanates, hydrazines)

Organic Compounds

- Hydrocarbons
  - -- Aliphatics
  - -- Olefins
  - -- Aromatics (benzene, toluene, xylene, etc.)
  - -- Polynuclear aromatic (benzo(a)pyrene, etc.)
- Oxygenated Hydrocarbons
  - -- Acids (acetic, benzoic, etc.)
  - -- Anhydrides
  - -- Ketones
  - -- Epoxides
  - -- Ethers
  - -- Lactones
  - -- Phenols (crosols, xylenols, etc.)

TABLE 4-3. Continued

  - Alcohols (methyl, etc.)
  - Peroxides
  - Polynuclear (oxa arenes, ring carbonyls)
  - Ozonides
  - Aldehydes (formaldehyde, etc.)
- Halogenated Hydrocarbons
  - Chloronated, polychloronated
  - Fluorinated
- Sulfur-containing Hydrocarbons
  - Mercaptans
  - Thiophenes
  - Heterocyclic/monocyclic (thio)
  - Polynuclear (thio arenes)
  - Alkyl sulfates
  - Sulfonic acids
  - Sulfoxides
  - Sulfones
- Nitrogen-containing Hydrocarbons
  - Amines
  - Aliphatic
  - Aromatic (analines, naphthylamines, etc.)
  - Heterocyclic monocylcic (aziridines, pyridines, pyrolles)
  - Nitro compounds (Dimethylnitrosamine, etc.)
  - Polynuclear
  - Aza arenes (acradene, etc.)

TABLE 4-3. Continued

- Organometallics (metal-containing hydrocarbons)
  - -- Metal carbonyls
  - -- Chelates
  - -- Sulfonates
  - -- Metal alkyls

Carbon Compounds

- Carbon
- Carbon monoxide
- Carbon dioxide
- Carbonates

Oxygen Compounds

- Ozone

Halogen Compounds

- Chlorides (HCl, etc.)
- Fluorides (HF, etc.)

Hydrogen Compounds

- Hydrogen ion (inorganic acids)

Trace Element Compounds

- Arsenic compounds
- Barium compounds
- Beryllium compounds
- Bismuth compounds
- Boron compounds
- Cadmium compounds
- Chromium compounds

TABLE 4-3. Concluded

- Cobalt compounds
- Copper compounds
- Fluorine compounds
- Gallium compounds
- Germanium compounds
- Lanthanum compounds
- Lead compounds
- Lithium compounds
- Manganese compounds
- Mercury compounds
- Nickel compounds
- Phosphorous compounds
- Scandium compounds
- Selenium compounds
- Strontium compounds
- Tin compounds
- Vanadium compounds
- Uranium compounds
- Ytterbium compounds
- Yttrium compounds
- Zinc compounds
- Zirconium compounds

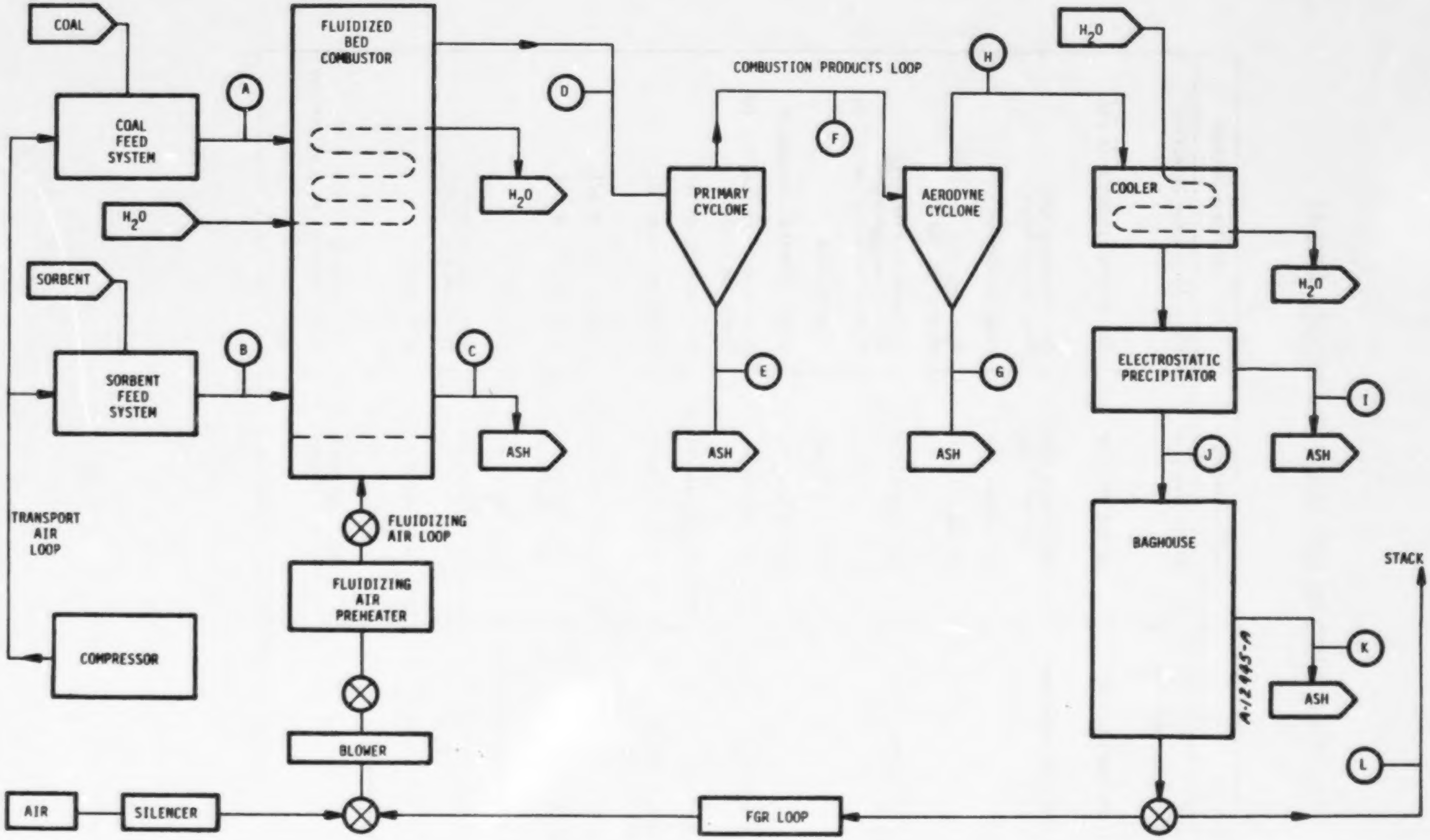

COAL
COAL FEED SYSTEM
A
H$_2$O
SORBENT
SORBENT FEED SYSTEM
B
TRANSPORT AIR LOOP
COMPRESSOR
FLUIDIZED BED COMBUSTOR
H$_2$O
C
ASH
FLUIDIZING AIR LOOP
FLUIDIZING AIR PREHEATER
BLOWER
AIR
SILENCER
D
COMBUSTION PRODUCTS LOOP
PRIMARY CYCLONE
E
ASH
F
AERODYNE CYCLONE
G
ASH
H
H$_2$O
COOLER
H$_2$O
ELECTROSTATIC PRECIPITATOR
I
ASH
J
BAGHOUSE
K
ASH
A-12445-A
STACK
L
FGR LOOP

Figure 4-1. FBC test rig sampling locations.

TABLE 4-4. SAMPLING AND ANALYTICAL METHODS SUMMARY

Species	Sampling Method	Analysis Method
Organic Compounds Total light hydrocarbons $[\Sigma(C_1 - C_6)]$	Online analyzer	Flame Ionization Detection (FID)
Separate light hydrocarbons ($C_1 - C_6$)	Online analyzer	Gas chromatography with FID
Middle to heavy hydrocarbons ($>C_7$)	SASS train XAD-2 sorbent trap	Gas chromatography - Mass spectrometry
NO/NO_x	Online analyzer	Chemiluminescence
CO/CO_2	Online analyzer	Nondispersive Infrared Absorption (NDIR)
Reduced sulfur compounds (H_2S, RSH, etc.)	Online analyzer	Coulemetric titration or Gas chromatography - Flame photometric detection
SO_2	Online analyzer	Fluorescence
O_2	Online analyzer	Electrochemical transducer
Nitrates and nitrites	SASS impingers	Calorimetric or Specific Ion Electrode (SIE)
Sulfites and sulfates	SASS particulate catch	Colorimetric or SIE
Reduced nitrogen compounds (ammonia, cyanides, etc.)	SASS impingers	Colorimetric or SIE
Carbonates	SASS particulate catch	Colorimetric or SIE
Chlorides and fluorides	SASS impingers NaOH absorption	Colorimetric or SIE
Hydrogen ion (inorganic acids)	SASS impingers	ph meter
Elemental sulfur	SASS particulate catch	Spark Source Mass Spectrometry (SSMS)
Carbon	SASS particulate catch	ASTM D3178
Trace element compounds		
Arsenic	SASS impingers (quartz probe)	Calorimetric
Barium		Atomic Absorption Spectroscopy (AAS)
Beryllium		AAS

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TABLE 4-4. Concluded

Species	Sampling Method	Analysis Method
Bismuth	SASS impingers (quartz probe)	AAS
Boron		Colorimetric
Cadmium		AAS
Chromium		AAS
Cobalt		AAS
Copper		AAS
Fluorine		SIE
Gallium		AAS
Germanium		AAS
Lanthanum		AAS
Lead		AAS
Lithium		AAS
Manganese		AAS
Mercury		Flameless Atomic Absorption Spectroscopy
Nickel		AAS
Phosphorous		AAS
Scandium		AAS
Selenium		Colorimetric
Strontium		Colorimetric
Tin		AAS
Vanadium		AAS
Uranium		AAS
Ytterbium		AAS
Yttrium		AAS
Zinc		AAS
Zirconium		AAS

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TABLE 4-5. SAMPLING LOCATIONS AND REQUIREMENTS

Sampling Location	Sampling Requirements
A -- FBC coal feed	Grab
B -- FBC sorbent feed	Grab
C -- Furnace bottom ash	Grab
D -- Primary cyclone inlet	Gaseous and particulate
E -- Primary cyclone ash	Grab
F -- Primary cyclone outlet/ Aerodyne cyclone inlet	Gaseous and particulate
G -- Aerodyne cyclone ash	Grab
H -- Aerodyne cyclone outlet/ electrostatic precipitator inlet	Gaseous and particulate
I -- Electrostatic precipitator ash	Grab
J -- Electrostatic precipitator outlet/baghouse inlet	Gaseous and particulate
K -- Baghouse ash	Grab
L -- Stack	Gaseous, particulate, opacity

accomplished either by continuous analyzers and one or any combination of SASS trains located throughout the effluent system. The specific need depends on the requirements of the research program.

Online Analysis Instrumentation

The following general remarks apply to all online sampling and analysis monitors.

Each pollutant species of interest which lends itself to online continuous monitoring, is capable of being measured with numerous commercially available instruments (90 or more in some cases). In addition, each family of instruments employs monitors using as many as ten operational principles. As an example, NO-NO_x instruments number over 40. Their principles of operation include colorimetric, ion-selective electrode, electrochemical cell, chemiluminescence, NDIR, nondispersive UV and visible absorption, and absorption spectroscopy. Naturally, instruments vary in price depending on various factors such as measurement method, reliability and durability. In many cases it is necessary to settle for less than maximum reliability (i.e., accuracy, specificity and sensitivity) because of limitations in time available for inspection, maintenance and repair that highly reliable instruments demand. This is especially true in stationary source monitoring in which the operating conditions may be quite hostile. However, this is not anticipated to be the case with the FBC test rig.

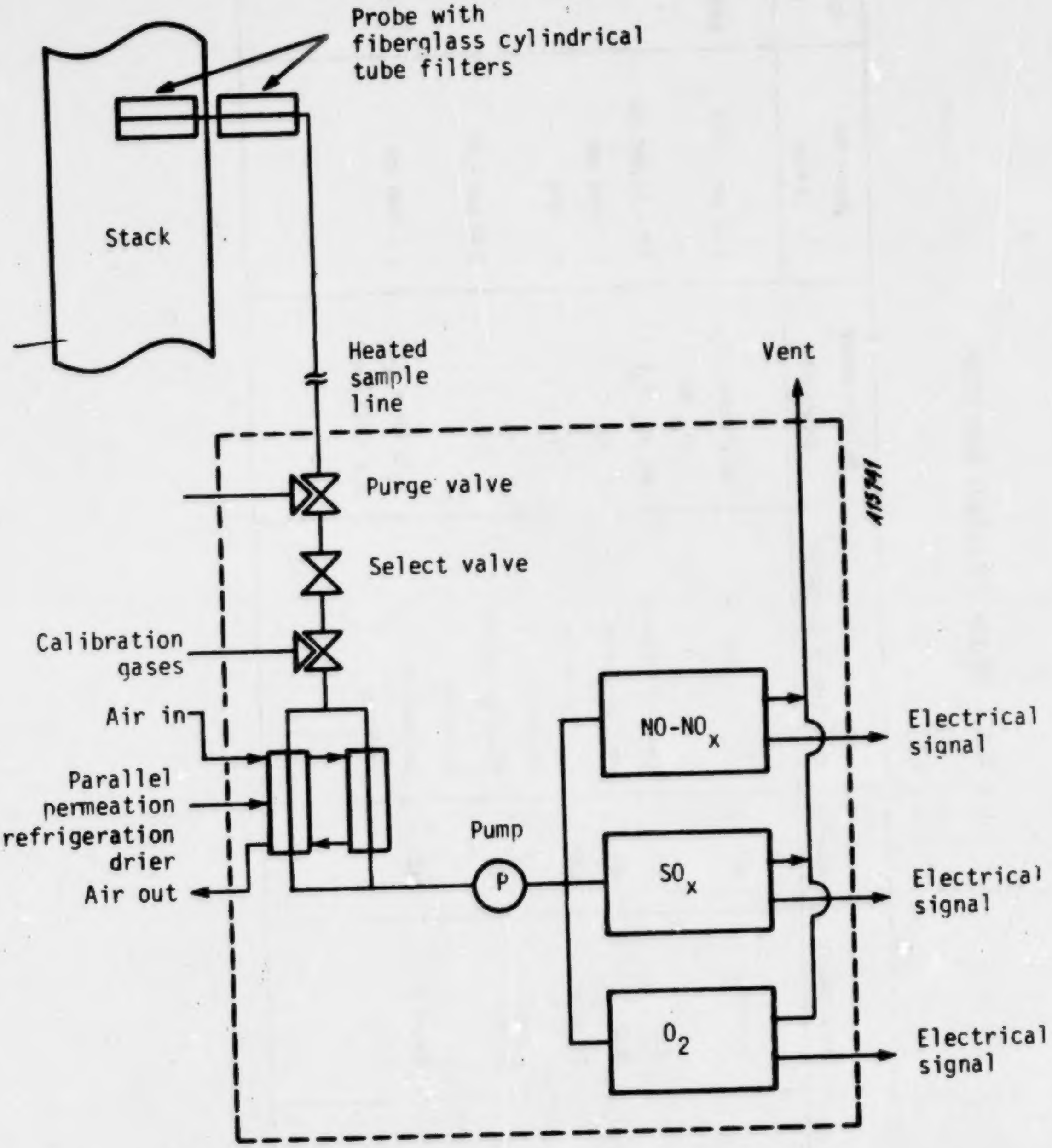
Multiparameter capabilities are becoming a common attribute in monitoring instrumentation. Use of such instruments offer the advantage of lower procurement, operational and maintenance costs compared with using several individual monitors each with a single pollutant measuring capability. However, due to the research-oriented nature of this task, it is desirable to be able to simultaneously measure and record various pollutant concentrations. This capability would enable researchers to observe and analyze relative pollutant concentration fluctuations under identical operating conditions. Consequently, separate instruments for each pollutant species to be monitored are recommended.

All recommended monitors require a certain degree of sample conditioning in which particles and moisture are removed before gases enter into the instrument. In general, the system components are: glass-fiber filters internal and external to the sampled flue, heat-traced sample line, permeation drier for water removal, vacuum source, and analytical instrumentation. Up to three monitors could use the same conditioning unit. Figure 4-2 details a typical system. Table 4-6 summarizes pertinent facts regarding the online analyzers recommended.

As noted in Section 1, there are certain online sampling and analysis instruments that are being strongly recommended for use on the fluidized bed combustor test rig due to their ease of operation, low cost, convenience and utility. The pollutants measured by these monitors are sulfur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and low molecular weight hydrocarbons (hydrocarbons $<C_6$). All of the recommended instruments are in common industrial use for process monitoring purposes and by source sampling contractors as continuous monitors for long-term research projects.

Low Molecular Weight Reduced Sulfur Compounds

Instrumentation for the measurement of low molecular weight reduced sulfur compounds is readily available, relatively inexpensive and can be operated by a technician with minimal training. The Barton Model 342


Probe with fiberglass cylindrical tube filters
Stack
Heated sample line
Vent
Purge valve
Select valve
Calibration gases
Air in
Parallel permeation or refrigeration drier
Air out
Pump
P
NO-NO$_x$
SO$_x$
O$_2$
Electrical signal
Electrical signal
Electrical signal

115741

Figure 4-2. Typical analyzer conditioning system.

TABLE 4-6. ONLINE POLLUTANT ANALYZERS

Pollutant	Manufacturer	Model	Principle of Operation	Multiparameter Capability	Measuring Range	Approximate Cost $
CO/CO_2	Beckman	865	NDIR	CO (Hexane, CO_2, SO_2, NO)	0.25 ppm - 100%	3000 to 4000
NO/NO_x	TECO	10A	Chemiluminescence	NO, NO_x (O_3)	0.1 - 10,000 ppm	5000
SO_2	TECO	40	UV fluorescence	SO_2	1 - 5000 ppm	6000
O_2	Teledyne	326A	Electrochemical transducer	O_2	0 - 100%	1400
Total hydrocarbons ($<C_6$)	Beckman	400	Flame ionization detection	THC	0.02 ppm - 5%	2000
Reduced sulfur compounds (H_2S, RSH, RSR, etc.)	Barton ITT	342	Coulemetric titration	H_2S; RSH + H_2S; H_2S + RSH + RSR	0 - 1000 ppm	5000

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Recording Sulfur Analyzer equipped with the Barton Model 302 Manual Analytical Filter is recommended for onsite measurements of the following sulfur compound groups: hydrogen sulfide; mercaptans and hydrogen sulfide; and sulfides, mercaptans, and hydrogen sulfide. Thus, specific determination can be made of H_2S, mercaptans, sulfides, and residual sulfur which includes sulfur dioxide. Included in the approximate base price of $5000 is the titration module, electronic control modules, and necessary accessories. A compatible external recorder is available for approximately $1100.

If more specific identification and quantification of reduced sulfur compounds is desired, an online, multicolumn, gas chromatograph would have to be used. The best detector for this purpose is the flame photometric type. A specific recommendation of which instrument is preferable cannot be made until the research effort objectives are better defined. Low molecular weight reduced sulfur compounds (such as H_2S, COS, RSH and RSSR) demand more complex online sampling and analysis instrumentation. Anything other than online sampling and analysis is precluded due to high reactivity.

$\underline{CO/CO_2}$

Carbon monoxide (CO) and carbon dioxide (CO_2) are best measured by the principle of nondispersive infrared absorption (NDIR). NDIR is the most commonly used method with its accuracy and dependability well established since the early 1970's. However, NDIR instruments are subject to interference from other gases, such as water and aromatics. The problem is overcome by using auxiliary absorption cells or optical filters which remove most of the radiation at wavelengths at which the interfering substances absorb. Beckman Instruments' Model 865 is recommended for application on the FBC test rig. This unit is mainly used for CO detection but it is also suitable for use in measuring CO_2, hexane, SO_2 and NO. However, minor modifications to the instrument become necessary for a multiparameter capability. The need to have this capability cannot be established until the research effort objectives are better defined.

SO_2–

Sulfur dioxide is best measured by Thermo Electron Corporation's (TECO) Model 40 SO_2 Analyzer. The principle of operation is based on the fluorescent emission of SO_2 molecules with ultraviolet light. The electromagnetic radiation emitted is proportional to the SO_2 concentration in the gas sample. The Model 40 is fully self-contained, requiring no external gases or chemical for operation. There is, however, a requirement for a gas conditioning system which removes condensible water and filters particulate matter.

Total Light Hydrocarbons ($\leq C_6$)

Flame Ionization Detection (FID) has widespread acceptance as the best method for measurement of total light hydrocarbons (i.e., $<C_6$). Acurex recommends the Beckman Instruments Inc. Model 400 THC Analyzer for use on the FBC test rig. This analyzer measures total hydrocarbons in the range 0.02 ppm to 5 percent using flame ionization detection.

NO/NO_x–

Nitric oxides and nitrogen dioxide (NO/NO_x) are best measured by chemiluminescence, the production of radiant emission upon the reaction of NO with ozone (O_3) supplied by a pulsed ozonator. The resulting radiation is detected by a photomultiplier tube which in turn emits an electrical signal for output to a recorder calibrated in ppm. The chemiluminescent reaction is applicable only to the direct measurement of

NO. For the detection of NO_x ($NO + NO_2$), conversion of NO_2 to NO is required. NO_2 is recorded as the difference between the NO and NO_x measurements. The recommended Thermo Electron Corporation's Model 10A NO to NO_x Chemiluminescent Analyzer, has this NO_2 to NO conversion capability. The unit is self-contained and requires only a few additional items for operation. They are:

- An O_2 source (bottled O_2 -- commercial purity)
- NO calibration gas (no span or zero gas other than room air is required)
- A vacuum source (~ 2 scfh)

O_2–

There are a number of adequate oxygen (O_2) analyzers on the market. Acurex has experience with and recommends the Teledyne Model 326A, an excellent general-purpose O_2 analyzer. The heart of the unit is an O_2 sensing cell. It is an electrochemical transducer requiring no attention other than periodic replacement (approximately once each year).

Source Assessment Sampling System

The bulk of the FBC test rig pollutant sampling should be done using the Source Assessment Sampling System (SASS). The capabilities of this system are:

- Measurement of particulate mass emission rate
- Particulate sizing distribution into four size ranges (i.e., $> 10\mu m$, $3\mu m$ to $10\mu m$, $1\mu m$ to $3\mu m$, and $< 1\mu m$)
- The collection of combined organic material
- The collection of volatile inorganic matter
- The collection of trace metals

The (SASS) sampling train (Figure 4-3) is an extension of Acurex's High Volume Stack Sampler (HVSS) and is considered to be the state of the art in source samplers. All of the components in the HVSS train are found in the SASS train with some important additions; they share the same probe, sample lines, impinger system, vacuum source, and control module. The SASS train has, in addition, particle size fractionating cyclones located in the filter oven (immediately following the sample probe) and an XAD-2 sorbent trap module (Figure 4-4). The XAD-2 sorbent trap is a porous polymer resin capable of adsorbing a broad range of organic species. It is an integral part of the gas treatment system which comprises a gas conditioner, XAD-2 sorbent trap, aqueous condensate collector, and temperature controller. After adsorption of the organic species by the XAD-2 sorbent trap, various organic fractions are desorbed by pentane extraction in Soxhlet apparatus.

The SASS train will be an indispensable research tool in working on the FBC test rig. Measuring the particulate fractional collection efficiencies of the various control devices can be readily and accurately performed with the SASS by simultaneously testing at the inlet and outlet of the control device. In addition, from just one test run, data can be collected regarding particle mass loadings and size distributions, and the fate of both organic and inorganic species within the control equipment.

The analytical methods required for the samples collected in the SASS train vary greatly in complexity and all are required to be done offsite. The following paragraphs deal with those methods. See Figure 4-5 for the SASS sampling and analysis scheme.

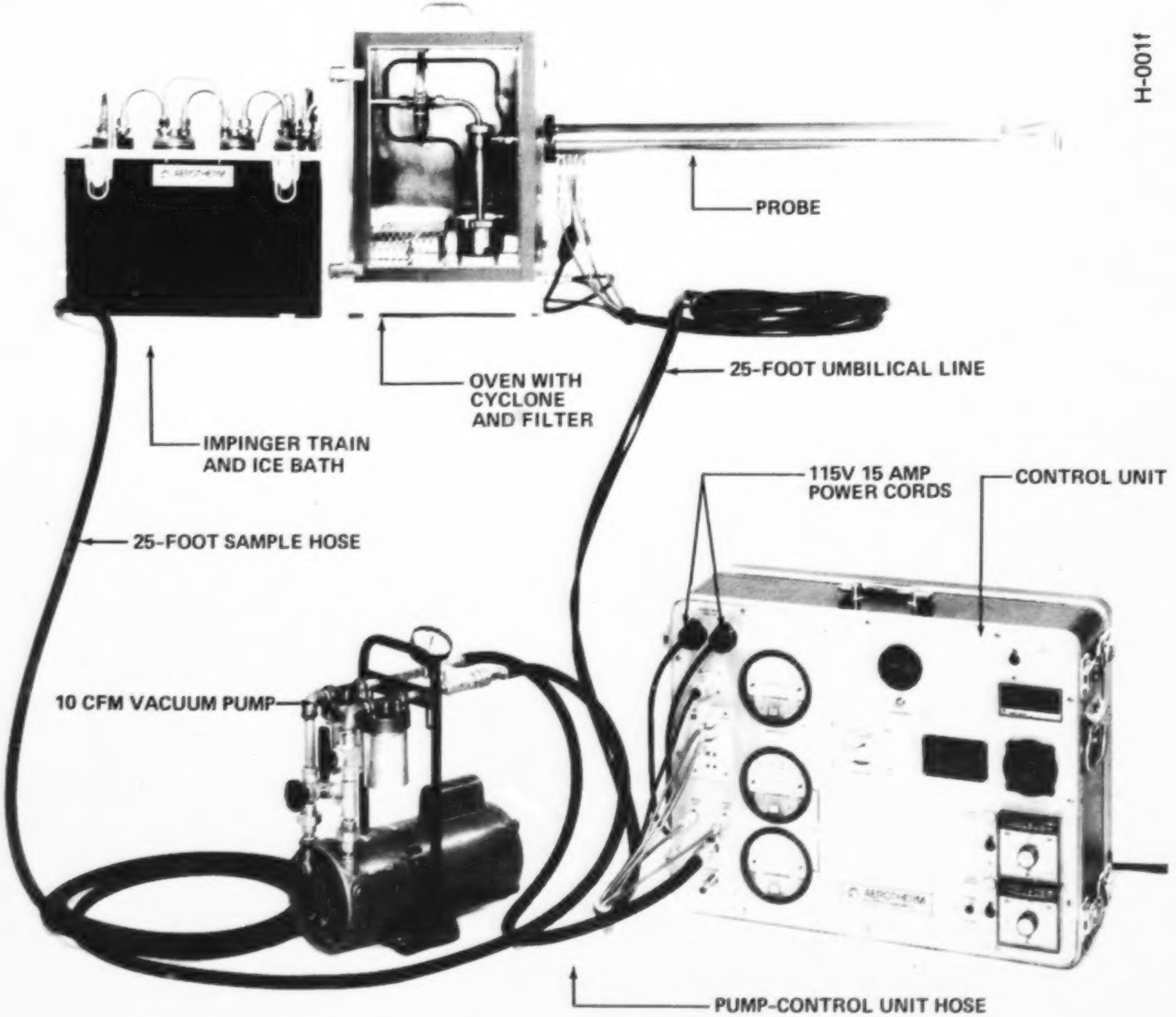
H-001f
PROBE
25-FOOT UMBILICAL LINE
OVEN WITH CYCLONE AND FILTER
IMPINGER TRAIN AND ICE BATH
115V 15 AMP POWER CORDS
CONTROL UNIT
25-FOOT SAMPLE HOSE
10 CFM VACUUM PUMP
PUMP-CONTROL UNIT HOSE

Figure 4-3. High Volume Stack Sampler (HVSS).

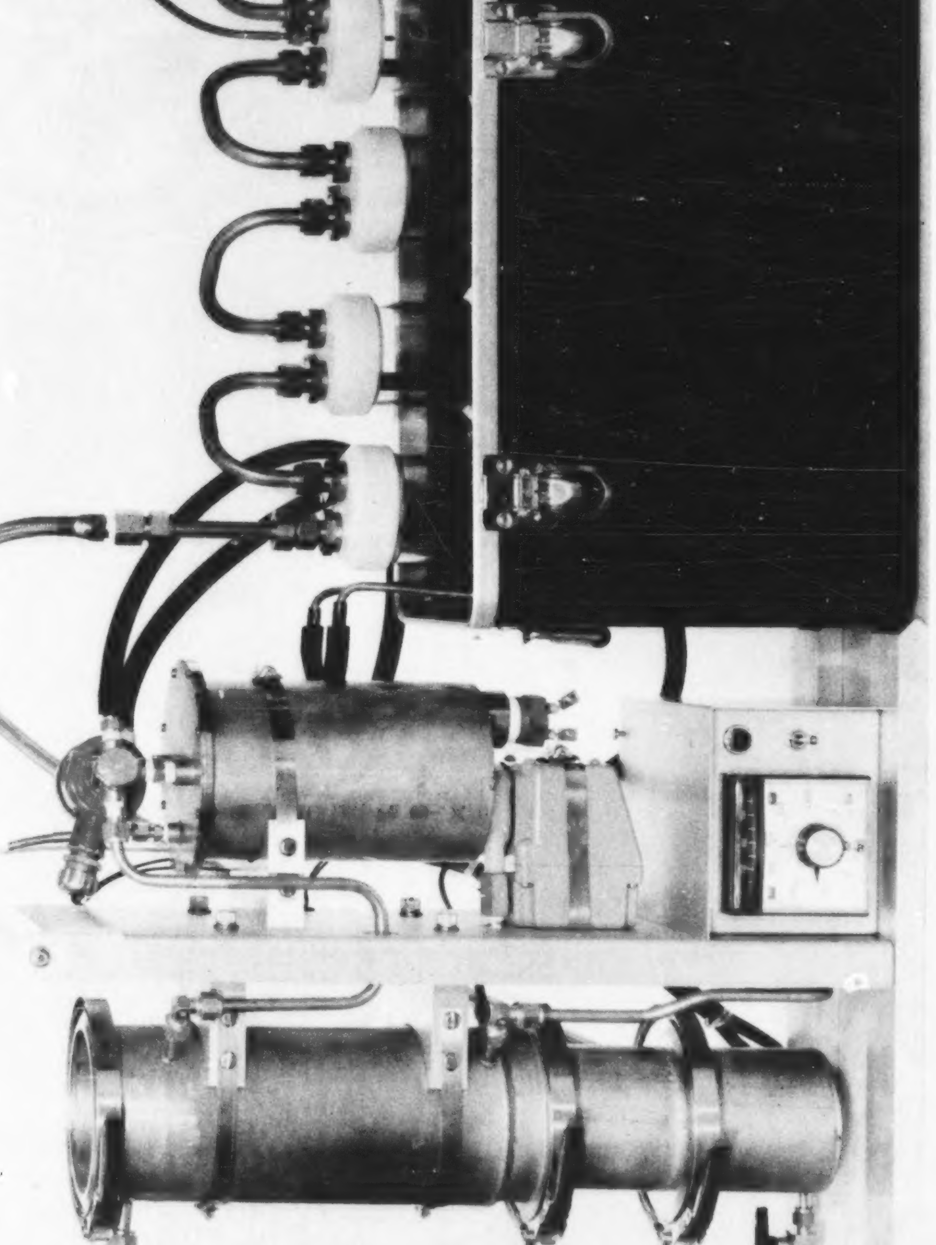

Figure 4-4. Tenax module and vaporous trace element impinger train.

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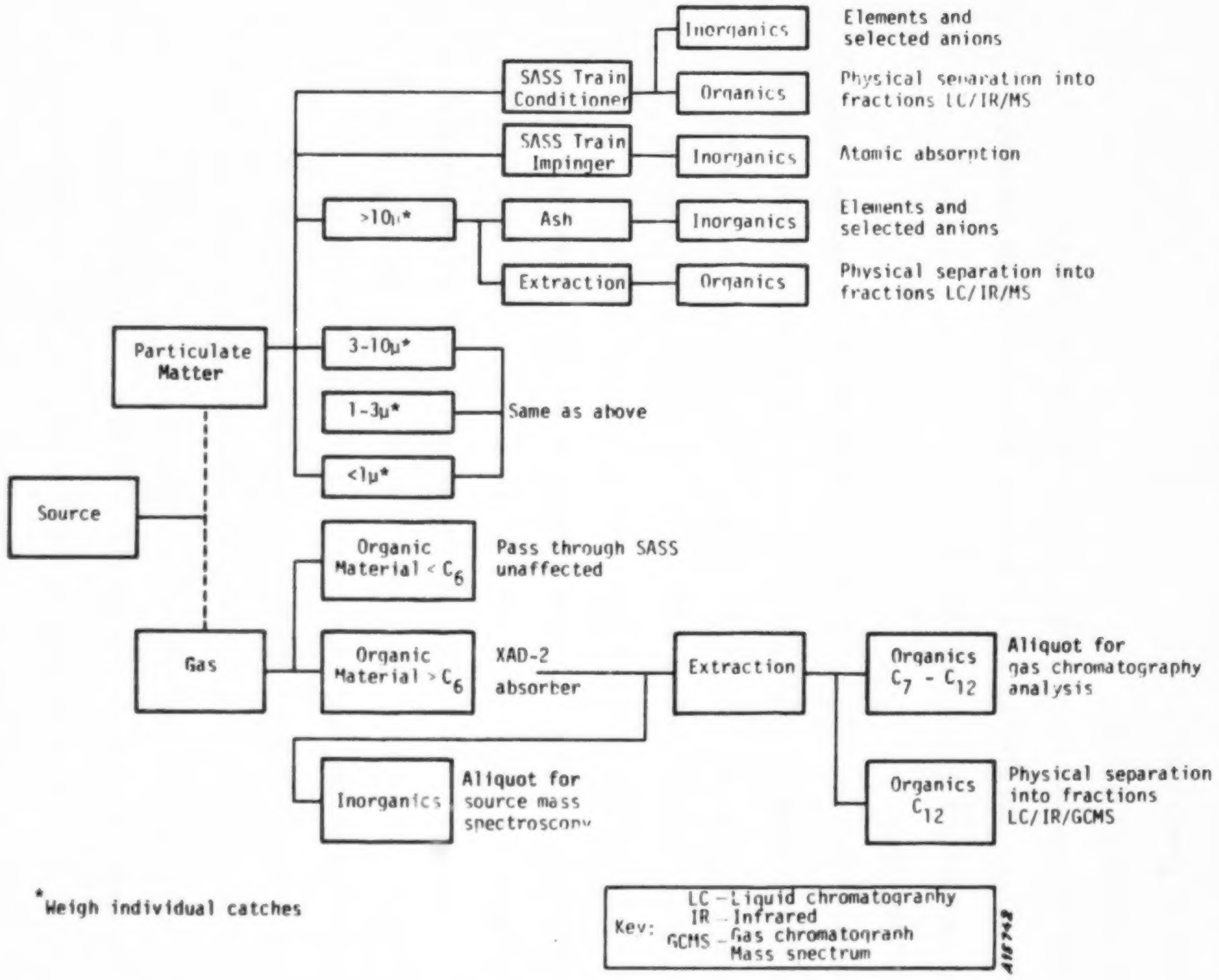
Source
Particulate Matter
Gas
SASS Train Conditioner
SASS Train Impinger
>10μ*
Ash
Extraction
Inorganics
Organics
Elements and selected anions
Physical separation into fractions LC/IR/MS
Atomic absorption
3-10μ*
1-3μ*
<1μ*
Same as above
Organic Material < C6
Pass through SASS unaffected
Organic Material > C6
XAD-2 absorber
Inorganics
Aliquot for source mass spectroscopy
Organics C7 - C12
Aliquot for gas chromatography analysis
Organics C12
Physical separation into fractions LC/IR/GCMS
Key: LC – Liquid chromatography
IR – Infrared
GCMS – Gas chromatograph Mass spectrum
A18742

*Weigh individual catches

Figure 4-5. SASS train sampling and analysis.

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Particulate Mass

The filter collection and residue left after rinsing and drying the "front half" (those exposed sample surfaces upstream of the filter) are determined gravimetrically.

Particle Size Distribution

The particulate weight from each cyclone is determined gravimetrically. Cumulative size distribution curves can be generated from the cyclone and filter collections.

XAD-2 Sorbent Trap

As a first step, the XAD-2 sorbent material is homogenized and physically separated into two portions. A 2-gram aliquot of one portion is used in Parr bomb combustion over HNO_3 to destroy all constituents but inorganics. The inorganic components, including possible trace elements, are then determined quantitatively by spark source mass spectrometry (SSMS). The remaining portion of the sorbent is extracted with pentane in a Soxhlet extractor. An aliquot of this organic extraction is analyzed for C_7 - C_{12} hydrocarbons by gas chromatography (GC) using a flame ionization detector (FID). An infrared (IR) spectrum is then obtained on the remaining organic extract. This enables determination of which of the eight potential organic fractions are present in the extract. This step saves unnecessary time spent on analyzing for fractions that are not present.

The separate organic fractions are divided by subjecting the extract to various solvents which exhibit an affinity for various organic classes. Silica gel liquid chromatography (LC) is the technique used in the separation procedure. Further identification of specific compounds within each fraction is performed by infrared (IR) spectrometry. To quantify compounds identified in a particular fraction, the sample is analyzed on a gas chromatograph-mass spectrometer (GC-MS).

2.1 LIQUIDS AND SOLIDS SAMPLING AND ANALYSIS

Solids

A complete and accurate material balance of the entire FBC test rig system demands careful solids sampling of the coal/sorbent feeds and the ash deposits from each control device. The sampling techniques, while straightforward, must be done correctly to ensure a homogeneous representative sample. Material size, consistency, and sample site vary widely so one method is not appropriate for all samples.

Manual grab sampling is required in all instances. Coal and sorbent can be sampled by taking four shovels from different locations in the storage pile and homogenizing. If possible, a better practice procedure is to take a shovelful of each feed material from the conveying system. This is more desirable than storage pile sampling due to the tendency in piles toward settling by particle size and density. A series of such grab samples should be taken over a period of time. In either case, a sample splitter should be used to reduce the size of the sample to a manageable level and to assume that a representative sample has been obtained.

Ash samples from the collectors are handled in much the same manner. If ash hoppers are present, representative samples should be taken periodically with either a pipe borer or auger sampler across the width of the hopper (or in some cases, vertically down the hopper).

Samples collected should be stored in airtight, high-density polyethylene containers until ready for analysis. Large samples should be placed in metal containers lined with polyethylene bags.

Coal, sorbent, and ash analytical methodology and equipment is widely available. Coal and ash analyses and methods are listed in Table 4-7. Preferred sources are Commercial Testing and Engineering in Chicago and Bituminous Coal Research in Washington.

Opacity Measurements

Opacity of the stack effluent gas has value as a relative measurement tool when "tuning" the FBC for the cleanest emissions visually. Two options are available:

- Using a trained certified observer to read opacity using the Ringelmann technique
- Installation of an opacity monitor which could continuously read and record smoke opacity. Numerous and comparable commercial units are readily available

TABLE 4-7. COAL AND ASH ANALYSES

Stream	Analysis	Sample Producer	Prep. Producer	Analysis	Analysis Procedure
Coal	Proximate	ASTM D2234	ASTM D2013	Moisture	ASTM D3173
				Ash	ASTM D3174
				Volatile Matter	ASTM D3175
				Fixed Carbon	ASTM D3172
Coal	Ultimate	ASTM D2234	ASTM D2013	Overall	ASTM D271
				C, H	ASTM D3178
				S	ASTM D3177
				N	ASTM D3179
				Ash	ASTM D3174
				O	ASTM D3176
				Moisture	ASTM D3173
				Cl	ASTM D2361
Coal	Size	ASTM D197		Size	ASTM D197-30
Ash	Sulfur			S	ASTM D1757 or
from					ASTM D271
bed					
	Proximate				ASTM D2795
	Trace			Trace Metals	Section
	Size	ASTM D197		Size	ASTM D197-30

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SECTION 5

TRAINING AND ACCEPTANCE TEST

To demonstrate the capabilities of the FBC test rig and its proper performance within the design parameters, an acceptance test was conducted upon completion of construction. Some minor operational problems were encountered that have since been corrected.

Prior to the training and test subsystems had been inspected and checked out to the extent practical, and the system had been operated by several hands. The quality of workmanship, materials, and fabrication had been verified to insure proper operation.

Training

A training program was conducted at the EPA's Research Triangle Park facility in which representatives of the EPA and Acurex Corporation participated. The facility was discussed in detail with reference made to the operations manual and the procedure outlined to derive a particular set of operating conditions. On the following two days the facility was started up, operated for several hours and shut down. On the second day of operation the assigned laboratory technician was permitted under supervision to operate the facility and gained sufficient confidence to operate the facility by himself.

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Acceptance Test

Three tests were conducted to demonstrate

- Startup, steady-state, and shutdown
- Firing at design point
- The operating range

Demonstration of Startup, Steady-State Operation and Shutdown

The facility was started up, operated and shut down as described in Section 4 of this report. All systems performed as expected with the exception of the solid feed system and the automatic bed height control.

The solid feed system pneumatic transport tube plugged several times and the sorbent and coal feed was not steady, resulting in substantial temperature fluctuations in the bed. The plugging of the pneumatic transport line could be traced to some large (1.5 cm dia.) pieces of sorbent that had not been removed by screening. The coal and sorbent also had a high moisture content and this was the cause of the uneven feed. Dry, screened material placed in the bin and run the next day substantially reduced these problems.

The automatic bed height control gage signal lines were clogged during the first test run and the solids dump valve could only be operated manually. The lines were cleaned out and proper signals were recorded on the second day. Due to the action of the bed, oscillations in the gage readings required signal damping. Signal damping, however, also resulted in slow response of the closing of the dump valve and substantial loss in the bed height.

The bed height control has since been modified in its logic. Its new timing controller activates an alarm when the bed reaches a preset value before the valve is opened. Closing of the valve is set by a timer 2 to 10 seconds later. This sequence can also only be activated once every 6 to 10 minutes.

The ash dump valve will also be opened upon a power failure in the Wing G facility to prevent fusing of the bed.

An air supply line to the valve burned through when a hot piece of sorbent sprayed on the line. This line was replaced with a copper tube.

Demonstration Firing at Design Point

Operation at a constant coal feed rate and bed temperature is vertical to obtain meaningful data when samples are withdrawn from the stack or other parts of the system.

The performance of the FBC test rig to operate at approximately 32 kg/hr (70 lbs/hr) and 873°C (1600°F) was relatively satisfactory within a ± 17°C (25°F) temperature band. Closer control would require the use of an automatic temperature feedback control on the coal feedrate.

It is noted here that the energy capacitance of the bed is small and that small variations in the coal feedrate ($\geq$ 1%) will have larger effects on the temperature variation than the ± 14°C (± 25°F) fluctuations observed. The particle size of the coal sorbent and the moisture content influence the feedrate and energy release rate due to bulk density variations and the latent heat of vaporization of water. Since these variables are very difficult to control or even undesirable to control, effective control can only be achieved by controlling the secondary effects, namely temperature in the bed. A dual set point controller lowering or raising the voltage for the coal feeder would accomplish this at a relatively low cost should this be desirable.

To increase the resolution on the solid feed rate controllers additional rheostats have also been installed to control the span.

Further test operations to date have shown the coal feed rtae to be accurately controllable and plugging with well screened material to be no problem.

Demonstration of Operating Range

Operation of the FBC test rig over its entire operating range within acceptable component operating conditions is only possible by reconfiguring the facility. Whether the facility can achieve all of the operating conditions specified can however be inferred if a judicious set of operating variables is selected and observed. The critical operating parameters that needed to be observed were maximum air, coal and sorbent flowrate and the maximum combustor temperature. The maximum air flow capability was verified when the system was started up to preheat the bed. Coal and sorbent flowrates had been verified before testing began and the bed was operated, although only for short durations up to 1050°C (1925°F). Since essentially zero flow can be achieved by all solids flows the limiting factor is the minimum flow through the blower. Pulsations in the blower have been observed only below the minimum required flow to meet all specified operating conditions.

In conclusion, the demonstration test showed that the operating condition specified in the statement of work can all be met although not all at the same time or in the same test rig configuration. Minor operating problems have been corrected. Certain procedures must be observed to insure stable, reliable solids feed system operation.

SECTION 6

RAW MATERIALS SOURCES, HANDLING, AND PRICES

Coal Selection

Since changes in coal properties have marked effects on the combustion process and on pollutant emissions, and since coal properties vary significantly from coal type, the testing of several different coals is essential to a good test program and to the understanding of combustion in the FBC. Important properties of interest include:

- Fuel nitrogen content, which is expected to have an important effect on FBC NO_x emissions and on NO_x control techniques (as it does in conventional combustors)
- Fuel sulfur, the retention of which by bed or fuel additives is usually a major goal, so that a study of the retention effectiveness of various additives for various coals is a primary part of most research programs; here it may be necessary to distinguish pyritic sulfur from organically bound sulfur
- Ash content which influences flyash amounts and ash retention
- Ash properties, such as fusion temperatures and chemical constituents, which affect ash retention and combustion properties.
- Other coal composition parameters, especially contents of alkali metals and trace metals, and acid base ratios, which influence fouling and corrosion
- General coal properties such as rank, volatiles content and heating value, which influence combustion behavior and ash retention

The selection of coals, however, cannot depend only on a "scientific" interest in the effects of property variations, particularly in a research program of specific objectives and limited scope, since the number of properties and effects to be studied is very large. Research programs in the FBC facility must concentrate on coals of present or future importance in the power production and industrial steam raising markets. This limits choices to three generic market types, each with reasonable restricted ranges of variation in properties.

- Appalachian Region High-Volatile Bituminous — coals in this class represent the single most used steam-raising coals in the United States and are generally regarded as the finest for conventional combustion techniques; substantial production increases are expected; this coal dominates Eastern markets.
- Interior Province, Eastern Region Bituminous — this coal dominates the Midwestern market area of the United States and is prominent in steam-raising applications.
- Northern Plains Province Subbituminous — economically the most attractive Western coal with substantial reserves; it has already achieved large market radius; substantial production increases are expected; it provides a low sulfur type.

To this list we added a lignite, which has a large market potential and represents an interesting high-ash, low-quality limit.

Table 6-1 briefly describes these four coals, presents the rationale for selecting each type, and identifies individual sources of supply and coal cost.

TABLE 6-1. SUMMARY OF SELECTED COALS

Class	Type	Source	Typical Properties Vol	FC	ASH	HV	S	N	Rationale	\$/ton[a]
Appalachian High-Volatile Bituminous	Pittsburg Seam #8 (high-volatile bituminous)	Consolidation Coal Pittsburg, E. Reichl V.P. Research, (412) 288-8700	38-40	50-57	5-8	13.4-14K	1.5-4.5	1.3-1.8	Highest Quality U.S. Coal; Wide Distribution and Future Expanded Production, High Sulfur, Highly Caking	\$26.50
Interior Province (High- & Medium-Volatile Bituminous)	Kentucky #9 Western Kentucky	Peabody Coal Co., O. Shelton, Mgr., W. Region, St. Louis (314) 342-3400	30-42	45-54	7-12	10-12K	2-5	1.2-1.8	In General Similar to Appalachian Coal; Widely Distributed; Especially in Midwestern State; High Sulfur; Noncaking	\$25.75
Mountain Province Subbituminous	Montana Subbituminous Power River Region	Peabody Coal Co., O. Shelton, Mgr., W. Region, St. Louis (314) 342-3400	44	46	9	8.6K	1.0	1.0	Increasing Distribution; Very Abundant; Expected to be Even More Available. Low in Sulfur; Noncaking	\$ 9.75
Mountain Province Lignite	N. Dakota Lignite	Consolidation Coal Co., Western Div. Velva Mine, Velva N. Dakota (303) 534-2100	43	48	9	6.8K	0.5	-	High Ash Content; Low Heating Value; Low Sulfur; Noncaking	\$ 6.05

[a] Cost refers to FOB mine and includes state sovereign tax

Coal Transport, Pulverization, and Storage

The four coals can be transported by rail in bottom dump cars from the respective mines to Cincinnati, Ohio for grinding by Hill and Griffith, Inc.[a]

Table 6-2 shows the railroads that have offered to transport the coal to Cincinnati, and the cost for each respective transport. Hill and Griffith has expressed reservations about grinding lignite with their equipment. This problem can be avoided by grinding this high ash content coal at Smith Facing in Cleveland, Ohio.

Coal Type	Grinding Company	Cost
Pittsburgh #8 Kentucky #9 Montana Subbituminous	Hill and Griffith Cincinnati, Ohio (513) 921-1075	$65/ton
North Dakota Lignite	Smith Facing Cleveland, Ohio (216) 861-6040	$60/ton

The cost includes pulverization, bagging, and palletization. Because grinding does not include screening of the coal, a mixture of different size coal is obtained. This mixture usually consists of:

4 to 6 percent – 20 mesh

20 to 25 percent – 60 mesh

35 to 55 percent – 100 mesh

15 to 40 percent – 200 mesh

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[a] Aerotherm experience on similar programs indicates that the selection of the pulverizer subcontractor is critical. Very few firms are prepared to handle research amounts of widely varying coals in the careful and scientific manner required by a research program. Hill and Griffith appears to represent the best selection from a very large number of firms considered in a multi-state region in the neighborhood of Raleigh-Durham and of most of the coal supply.

TABLE 6-2. COAL TRANSPORTATION COSTS FROM MINE TO CINCINNATI

Minimum Load Tons	Coal Type	Railroad	Mine Location	Total Cost $
60	Pittsburg #8	Monogahela	Fairview, W.V.A.	585
60	Kentucky#9	Illinois Central Gulf	Ohio County, KY Fordsville	500
60	Montana Subbituminous	Burlington Northern	Colstrip, MN	3,630[a]
25	North Dakota Lignite	Soo Line	Velva, ND	1,245[b]

[a] Three routes Colstrip MN — Minneapolis — \$35.41/ton
Minneapolis — Chicago — \$14.06/ton
Chicago — Cincinnati — \$11.01/ton

[b] Clan note = \$49.80/ton

A screening process permits uniform derived size of the pulverized coal, but adds significantly to pulverization costs because of time involved and coal wastage. Bagged coal would be transported to Raleigh-Durham by truck at about $36 per ton.

The indicated tonnage of coal supply represents nominally a 2- to 4-year supply at expected testing schedules. If less than this turns out to be required, a modest amount of improvisation usually succeeds in selling the excess, either to the pulverization firm or to local users.

Sorbent Selection, Pulverization, and Storage

The following criteria influence the choice of sorbent stone:

- Acceptable properties for sulfur removal
- Attrition resistance
- Trace element emission characteristics
- Regeneration characteristics
- Suitability of spent sorbent for final processing and disposal
- Economic availability of the stone

Fluidized-bed experimentation and modeling has attempted to develop quantitative guidelines for these criteria, relating these guidelines to properties of the stone and to combustion and heat transfer conditions in the fluidized bed. The results to date provide no definitive information, however, and give very little practical guidance in stone selection. For sulfur capture, limestone is generally more effective than dolomite at 1 atmosphere, and partial or total calcining appears to be helpful in most cases. (For pressures greater than 1 atmosphere, calcining appears required for limestone and very useful for dolomite in most, but not all, cases.) For the other criteria above, essentially no consistent guidance is available.

For costing purposes, therefore, we select a single limestone and a single dolomite, both of which have been extensively tested in earlier programs: Limestone 1359 and Dolomite 1357. Table 6-3 gives relevant properties. Due to their different calcium content, each has a different

TABLE 6-3. TYPICAL ANALYSES OF LIMESTONES AND DOLOMITES

Component	Composition %				
	Dolomite 1337	U.K. Dolomite	Limestone 18	Limestone 1359	U.K. Limestone
CaO	28.9	29.3	45.7	55.7	55.4
MgO	22.9	21.5	1.4	0.3	0.3
$H_2O + CO_2$	47.4	46.3	36.6	43.6	43.5
SiO_2	0.5	----	13.6	0.5	0.7
Fe_2O_3	0.2	----	0.3	0.1	0.1
SO_3	----	0.1	----	----	----
Total	99.9	97.2	97.6	100.2	99.8

The sources of those materials were:

Limestone 18: Supplied by Fuller Industries Inc., Fort Meyers, Florida. This has been referred to as "U.S. Limestone No. 18" or "T. 18" in interim reports.

Limestone 1359: Supplied by M. J. Grove Lime Co., Stephens City, Virginia and prepared at the Argonne National Laboratory. This has been referred to as "Argonne" limestone or "Limestone 1359" in interim reports.

U.K. Limestone: Supplied by J. Gregory & Sons, Kidsgrove, Stoke-on-Trent.

U.S. Dolomite 1337: Supplied by Charles Pfizer & Co., Gibonsburg, Ohio.

U.K. Dolomite: Supplied by Steetly (Manufacturing) Ltd., Worksop, Notts.

effect on sulfur oxide retention. Table 6-4 shows absorbent sources with cost of product and cost of shipping. The dolomite sorbent, low calcium content, can be furnished in three sizes. The cost of pulverized size, 50 to 55 percent, 200 mesh has been reported in the table. The sorbent will be bagged for storage and shipped to Raleigh-Durham, North Carolina, by Charles Pfizer and Company. The limestone sorbent is supplied by Grove Lime Company in 95 percent, 100-mesh size, but transport would have to be made in an enclosed truck, since the limestone is not bagged. Bagging the limestone will bring the price to approximately $50/ton. Larger size limestone (0.16 to 0.32 cm (1/16 to 1/8 inch)), bagged, will cost as much as $100/ton, because it requires screening to obtain a uniform size. Freight cost of bulk material will be on a minimum of 20 tons transport; therefore the freight cost will be $400.

Calcining or other pretreatment should be handled by EPA or the research program contractor to assure appropriate control and characterization.

TABLE 6-4. SOURCE AND COST OF SORBENT MATERIALS

Absorbent	Source	Cost	Freight to N.C.
Dolomite 1337	Charles Pfizer & Co. Gibsonburg, OH (419) 637-2101	\$17.78/ton[a] for first 8 tons	~\$30/ton
Limestone 1359	M.J. Grove Lime Co. Stephen City, VA (703) 869-2700 (301) 662-1181	\$5.00/ton[b]	\$20/ton

[a] Includes cost of bagging and pelletizing

[b] Bulk not bagged

SECTION 7

SAMPLING SUPPORT FEATURES

The basic purpose of the FBC test rig is to evaluate the effect of changes in operating conditions on emissions. To permit sampling at significant locations, 3-inch ports are provided at the locations noted in Figure 7-1 for the purpose elaborated in Table 7-1.

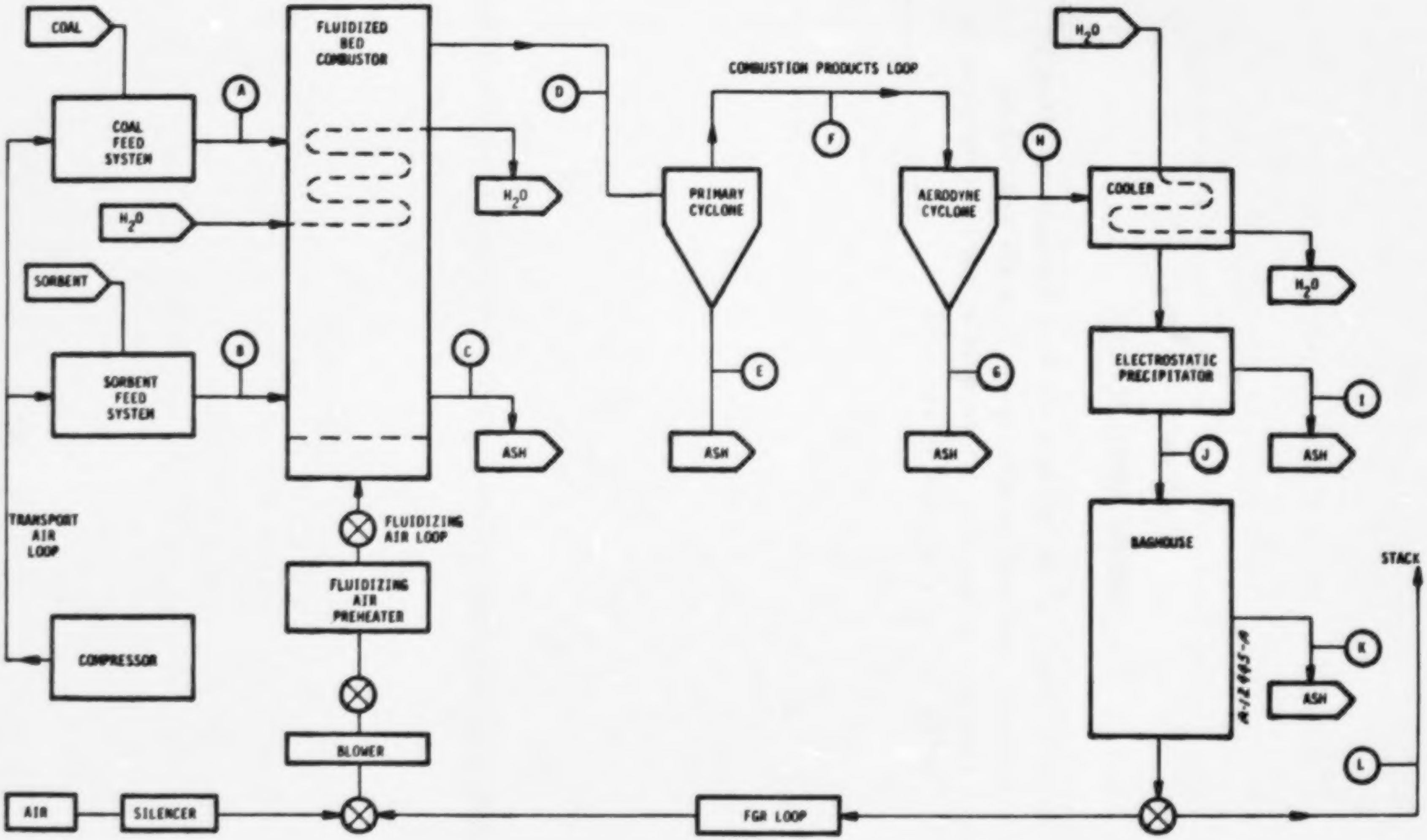
COAL
COAL FEED SYSTEM
A
FLUIDIZED BED COMBUSTOR
D
COMBUSTION PRODUCTS LOOP
H$_2$O
H$_2$O
F
H
H$_2$O
SORBENT
PRIMARY CYCLONE
AERODYNE CYCLONE
COOLER
H$_2$O
B
SORBENT FEED SYSTEM
C
E
G
ELECTROSTATIC PRECIPITATOR
I
ASH
ASH
ASH
J
ASH
TRANSPORT AIR LOOP
FLUIDIZING AIR LOOP
FLUIDIZING AIR PREHEATER
BAGHOUSE
STACK
COMPRESSOR
A-12445-A
K
ASH
BLOWER
L
AIR
SILENCER
FGR LOOP

Figure 7-1. FBC test rig sampling locations.

TABLE 7-1. SAMPLING LOCATIONS AND REQUIREMENTS

Sampling Location	Sampling Requirements
A — Furnace coal feed	Grab
B — Furnace sorbent feed	Grab
C — Furnace bottom ash	Grab
D — Primary cyclone inlet	Gaseous and particulate
E — Primary cyclone ash	Grab
F — Primary cyclone outlet/ Aerodyne cyclone inlet	Gaseous and particulate
G — Aerodyne cyclone ash	Grab
H — Aerodyne cyclone outlet/ electrostatic precipitator inlet	Gaseous and particulate
I — Electrostatic precipitator	Grab
J — Electrostatic precipitator outlet/baghouse inlet	Gaseous and particulate
K — Baghouse ash	Grab
L — Stack	Gaseous, particulate, opacity